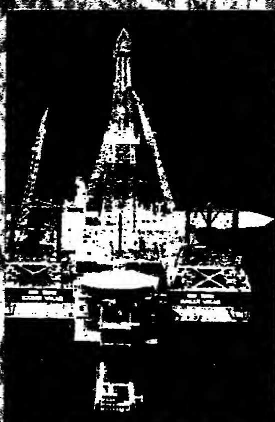
Energy and Food Security

Advances in Science for Sustainable Environment and Development in India During the Next Decade



Editors

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New Delhi India

ENERGY AND FOOD SECURITY

ADVANCES IN SCIENCE
FOR
SUSTAINABLE ENVIRONMENT AND DEVELOPMENT IN INDIA DURING THE NEXT DECADE

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FOREWORD

The Indian National Science Academy has been promoting activities in areas of considerable interest where specific advances in Science and Technology impact on Society. These have resulted in Seminars, Symposia and Conferences in the country and in the constitution of groups of experts to prepare authoritative Reports on various topics of societal development. The Academy has participated in major International Conferences of worldwide interest in co-operation with National Academies of several countries. An Inter Academy Panel of Academies of eighty countries has been functioning with India and USA as Co-Chairs. A Report prepared by the panel on Population was a major contribution to UN conference on Population in Cairo. A similar Report was also evolved and presented at the UN Conference on Large Urban Cities held in Istanbul. A world Conference on Sustainable Environment in the next Millenium was held in Tokyo since 14 to 16 May 2000, where representatives of eighty National Science Academies as well as renowned Economists participated. Recognising the need for continued dialogue, an Inter Academy Council has been established.

The Indian National Science Academy has organised Conferences on topics such as the Guidelines on the Standards and Care of Animal Houses and use of Animals in Scientific Research, Intellectual Property Rights in Advances in Biology, Advances in Progress in Specified Human Health Issues, Ocean Science, Information Technology in Education and Research, the Indian Human Heritage,Deccan Heritage, Perspectives in Global Science and Technology in Telecommunications, Conserving Biodiversity for Sustainable Development, Advances in Space Physics and Advances in Informatics. The Academy has bilateral co-operation and Scientists Exchange Agreements with Academies and Scientific Research Councils of thirty countries. In seminars on the topics listed above, there has been participation by distinguished leaders in Economics, Sociology, Anthropology, Agriculture, Energy, Planning, Historical Studies, Education and International Relations; Researchers in Industry, Chief Executives, Directors in Companies as well as Senior Civil Servants.

Guided by the then President Professor G. Mehta and the Council, the Academy promoted a Seminar on Advances in Science for Sustainable Development in the next Decade with emphasis on Energy and Food Security in India. Held in Ahmedabad in 19 Dec., 1999, Dr. S. Varadarajan, former President of the Academy acted as the Convener. The discussions covered perspectives on energy emerging from hydrocarbon and coal as well as on adequate food to the growing population while adhering to communities for prevention of global warming. A number of

scientists, economists and social scientists responded to the invitation of the Academy and the present publication results from the presentations made. Several Fellows of the Academy as well as leaders from petroleum exploration and processing, Coal, Electrical Power and Renewable Energy-organisations contributed to the discussions. Professor G. Mehta inaugurated the Seminar and Professor M.M. Sharma, former President of the Academy enumerated the successful pilot scale demonstration of *in situ* gasification of deep underground coal in Western India.

The publication indicates opportunities to achieve sustainable development for the countries in the New Millenium from many innovations and scientific advances. Each of these would merit further attention for early action.

The Academy is highly appreciative of the contributors to the contents of the Volume and especially to Professor S.K. Malik, Fellow of the Academy and Editor of Publications. His untimely demise, a great loss to the Academy and to Science in India, led to the publication being delayed. The task of collecting all articles and editing was completed by Dr. S. Varadarajan.

M.V.S. Valiathan
President, INSA

May 02, 2002

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S. Varadarajan

INTRODUCTION

The success in the past five decades in meeting many basic needs in India are commendable. The large increase in population in the next two decades would result in very substantial increases in needs of energy and food while fulfilling aspirations for economic growth with virtual elimination of poverty.While meeting such needs of high order it is vital to ensure preservation and enhancement of environmental quality in land, water, marine systems and atmosphere. These present entirely new challenges to Science and Technology in achieving Sustainable Development. An overview of the many relevant factors such as population, land and water resources, energy and food is presented.

POPULATION

In Table I, estimates of population in India and land availability for agriculture are listed.

Table I

Year	Population Million (Rural)	Land Mill ha. Irrigated	Land Mill.ha Cultivated
1947	350 (305)	25	40
2001	1000 (700)	70	142
2010	1175	75	ca. 140
2020	1340	80	cc. 140

The urban population estimated at about 45 million in 1947 may increase to 300 million in 2000 and is expected to grow to about 450 million in 2010. Further changes would depend on opportunities for gainful employment in rural areas. Rapid increases in urban population, as in many countries all over the world seem probable. Several cities with populations of 15 million and above are already emerging in the country.

The world Population has doubled from 3000 million in 1960 in the four decades to 6000 million in 1999 with Asia accounting for 3500 million. China and India currently have the highest total. Attention in India to healthcare during the last five decades and especially in the past two decades has led to substantial success in elimination of many communicable diseases and reduction in mortality among infants in the first year after birth and in children below five years of age. These have contributed to notable increases in expectancy of life at birth. Unlike in Developed Countries, a large section of the total population is below the age of 20 in many States of the Union of India and will contribute to growth in numbers. The quality of life based on a variety of factors has been estimated by the United Nations Development Programme in the Human Development Report 1998. It ranks the Developed Countries in North America, Western Europe, Scandinavia and Australia as well as Japan and South Korea as high. Among the Eastern and Pacific Asian countries, Singapore, Thailand, Malaysia are among those with higher ranking. China and India are not yet reaching higher indices although their developments have been quite noteworthy.

ENERGY

Economic advances and Development with growing industrial production, movement to urban centres and demand for services for water housing, transport, education and communication result in energy demand in electricity, coal and petroleum products. The growth in India in coal and petroleum products has been therefore necessary as can be seen in Table II. Oil and Natural Gas are largely imported. Some coal import is also envisaged.

Table II

	Coal Mill.Tonns	Total Petroleum Mill. Tones	Petroleum Oil Import Mill. Tonnes	Natural Gas Mill.C.M.
1950	30	1	1	—
2001	320	100	75	15730
2010	500	220	200	20900

Energy Development in the past two decades has been impressive. India with a large rural population at the time of independence used by products of agriculture and forestry and biomass for home use. While this continues, the percentage of biomass in total energy has decreased from 65 per cent in 1977 to 55 in 1987 and to 48 per cent in 1997. Electrical energy generation has increased substantially in the twenty years (Table III).

Table III

Year	Thermal Power	Billion kwh Hydropower	Nuclear and Wind Power	Total
1977	41	41	2	84
1987	139	57	4	200
1997	330	72	10	410

The power generation capacities have been increased very markably during the last two decades, especially in the coal and lignite based thermal power. Such investments would continue to meet the ever increasing demands as can be seen below (Table IV).

Table IV : Capacity Thousand MW

	1997	1987	1997
Thermal	9.1	32.7	61.2
Hydro	6.9	16.0	21.6
Nuclear	0.6	1.3	2.2
Total	16.5	50.0	85.0

Energy consumption in India is as yet low as compared to Developed Countries as well as several Developing Countries as is evident from the Table below. The total energy consumption per capita in all forms (hydro, thermal and nuclear electricity, coal, oil) is expressed for convenience as Kilogram of oil equivalent per annum. The Human Development Index Ranking is also shown to reflect the possible relationship to such energy consumption.

Table V

Country	HDI	Electricity Bill kwh	Commercial Energy Consumption per capita Annual Kilogram oil
USA	3	3497	8051
UK	10	365	3992
Malaysia	56	53	1950
Thailand	67	92	487
Brazil	79	104	896
Sri Lanka	90	4	305
China	98	1078	902
Indonesia	105	74	402
Vietnam	110	16	448
India	132	434	476

It is clear, for improving quality of life, a high rate of economic growth of about 7 to 8 per cent per annum is considered essential. For an increase of population in the next decade of the order of 1.7 per cent per annum, energy availability increase of about 8.0 to 10.0 per cent is essential. Such a large increase has to be continued with further improvements in environmental quality. The opportunities for meeting these objectives are briefly outlined.

MEETING ENERGY DEMAND

From the above, the demand for electricity would increase from about 400 billion kwh in 1997 to about 1500 billion kwh in 2012. Much of it would be based on coal/ lignite with some contribution from petroleum and gas. There is also considerable opportunity for growth of nuclear power. The technology for power generation from coal and lignite has been improved and there are power plants with 1000 to 2000 MW in each location. Coal and lignite remain the most important sources for thermal power. Newer machinery with large capacity for underground mining is being introduced for higher productivity replacing human labour and open cast mining. Washeries have lowered the quantum of ash in coal for thermal plants. Power generation closer to mining areas reduces the requirement for transport in railways. This has to be matched by higher efficiency and lower loss in transmission to the power consuming areas. High Voltage Direct Current transmission to reduce losses has been demonstrated. The efficiency in generation in coal based power plants has to be greatly improved with replacement of older machinery. Thermal power generation in such plants is designed on the basis of operation for 6000hrs per annum compared to operation of 8000hrs in oil refinery, petrochemicals, fertilisers and nuclear power.

India has gained much confidence in the field of petroleum and natural gas in the last four decades and in contributing to energy requirements in the transport and domestic sectors. Although oil was discovered in the late nineteenth century at Digbhoi in Northeast India, a small oil refinery was established in 1933. New oil and gas field was discovered by the persistant efforts of the Oil and Natural Gas Commission established by Government of India in 1956. Indian geological scientists identified oil and gas early in 1963 in Western India onshore and a Refinery was formed in Baroda (now renamed Vadodara), close to Ahmedabad in Gujarat where this Annual Meeting and Seminar of the Indian National Science Academy is being held. Further persistant exploration efforts by Indian Scientists have led discovery of oil and gas offshore, establishment of pipeline transport. The formation of Government owned oil refining, distribution of petroleum products throughout the country during only three decades has produced benefits and public awareness. The Scientific Research has been transformed ably into technology and engineering for processes and for capabilities in design of reactors, fractionation

to quality, full evaluation of heat transfer, energy optimization. In addition, skills have been developed for fabrication of complex high technology equipment of high precision, safety, erection, test methods as well as commissioning and operation. Within a short span of two decades, oil and gas have emerged as key components in National energy. A brief account of these developments and of the strategy being developed is presented.

The share of oil and gas in energy sector in India is about 40 per cent presently. The demand is growing at an annual rate of 7 per cent. With the second largest population, India is a major consumer ranked twelfth in the world and may emerge as the fifth largest consumer in two decades. Table VI provides estimates of demand for oil and gas. Local production is as yet insufficient. Even with further efforts at exploration and possible discovery of new sources, the demand will far exceed the local production as illustrated in the Table.

Table VI

	Oil and Products Mill T.		Natural Gas (Mill. Metric. Cum. Mtrs/Day)	
Year	Demand	Local Production	Demand	Production
1997	84	34	100	55
2000	110	37	100	65
2010	230	45	200	40
2020	370	60	260	35

The production envisaged in 2010 and 2020 of crude is uncertain and is dependent on success in new measures. Demand may be higher than outlined. Demand for natural gas is substantially higher and the figures mentioned above are based on facilities for import and distribution. The strategy for exploration calls for increased and extensive investigation especially offshore in the extended western offshore and in the higher depth ocean beyond in the west as well as in the eastern deep water offshore with newer techniques involving acquisition of seismic data and data processing. These require high risk capital investment and new science technology capabilifies. Exploration by foreign companies is also included.

Natural gas is emerging as a fuel to meet the environmental standards of the future and as the new material for chemicals and in production of metals and metal products of high quality. The scientific research for the future offers many possibilities. Among these is coal bed methane (CBM) found in coal seams. This is as yet untapped. Only the USA has successfully demonstrated recently commercial production. Many countries in Europe are continuing efforts. There is need to intensify efforts in India. There are reported presence of such gas in Damodar Valley, Jharia, Bokaro and Raniganj.

The present demands are met in part by import of liquified natural gas (LNG) by ships from Gulf, evaporation of liquid in pipeline heat exchangers at sea near port and transport of compressed natural gas (CNG) by pipelines. These are demanding of port facilities and safety measures. The quantities thus imported and conveyed in pipeline are not large as yet and there are proposals for increase of twenty fold or more to meet needs after careful review. The absolute reliability of transport of LNG by ships across the ocean, unloading at coastal facility and conveyance overland to designated consumption urban centres has to be analysed and compared to the alternative of liquid petroleum products.

CONSERVATION FROM TECHNOLOGICAL ADVANCE

Electrical Power generation, transmission, distribution and consumption standards were originally evolved several decades ago on the basis of then demand, availability and systems in consumption. With the increase in costs of basic energy materials and the capital costs, the delivered price is being constantly increased by Power Companies and Boards. Technological advances for efficiency in generation and transmission are taking place. These are coupled with the standards for environment. In the case of coal, gasification and combined cycle operation has been demonstrated on pilot scale by the Indian Institute of Chemical Technology. While there is a higher capital investment, there is also higher quantum of power generation from the same amount of coal and in addition, there is virtual total elimination of suspended dust particles into atmosphere. These are described in the article in this volume by Dr. K V Raghavan, Director of the Institute. The larger scale operation in a similar manner by Bharat Heavy Electricals Limited is recorded in the article by K Basu and N V S Ramani on Integrated Gasification Combined Cycle in this volume. Further larger scale operations would ensure continued use of coal for electrical power while meeting rigorous environmental standards.

The High Voltage Direct Transmission of Power across vast distances is a major development already demonstrated. Such a technology permits power generation close to the major coal mines and deposits in Bihar and West Bengal and availability of power at other parts to meet demand. The Transmission and Distribution losses presently are said to be of the order of 40 percent and these need reduction.

As has been stated, the contribution for electric power from hydrosystems while increasing in the five decades form a lower percentage of national consumption Hydropower is related to seasons and release of water for agriculture. The total demands are not uniform during the day or seasons. Industry is provided encouragement to utilize power during off peak hours with lower tariffs, so that the power consumption may be more uniform than presently possible.

Major advances are also being made by Regional Integration of Power Generation and consumption to assist conservation and to increase fuller operation of thermal power plants to installed capacities. The aim eventually is to establish a National Grid Integration, now possible with modern telecommunication and computerised Information Technology and controls. Various States had made power available to irrigation for agriculture with nominal or no payment, a step not appropriate for efficiency and conservation. There are national debates on such a subsidized power. The relationship between energy and food production is a major debate. In addition to electrical power, petroleum products are also provided at special rates for irrigation as well as to industrial units engaged in manufacture of fertilizers.

NEW SOURCES OF ENERGY

i) Nuclear Power

A major National Development has been in the advances in Science and Technology for generation of nuclear power with increasing self reliance. From earlier developments with power generation from enriched uranium and light water reactors. India has been able to develop on its own, natural uranium Pressurised Heavy Water Reactors. The technology in all aspects including mining fuel, metallurgy for fabrication and loading, controls and operation have been perfected in the last two decades for 220 MW nuclear power generation and will be leading to 500 MW capacity reactors. India has also developed the technology for manufacture of Heavy Water with Hydrogen Sulphide with safety, efficiency to meet all needs and permit some exports. It is also envisaged that from the products from such generation and separation of highly radioactive plutonium and depleted uranium, a programme of Fast Bed Breeder Reactors would be established, eventually leading to the use of Thorium, available in abundance in India and its conversion to uranium 233. The efficiency in operation in the PHWR has been high. Nuclear power generation has to be constant and has to be combined with power from coal, oil and gas to meet varying demands. A major plan for achieving Nuclear Power Capacity of 10,000 MW in a decade and 20,000 MW in two decades is being pursued. These have been recorded in the Five Year Plans and in other publications such as Innovatives India Science and Technology Review. A brief outline of possible contribution to national needs of energy from nuclear power is given below:

Year	Capacity in MW	Current and Additions
1998	1500	Tarapur Rajasthan Kalpakkam
2001	2720	Additional PHWR
2002	3720	Additional PHWR 2 X 500 MW
2003	6700	PHWR Russian PFBR
2010	10,000	PHWR
2020	20,000	

ii) Gas Hydrates

A major potential sources of natural gas is from gas hydrates identified in the Western India Bombay Offshore in the extended basin from which oil and gas are already being supplied from fixed platforms. There may be also such occurence in other western areas and in East Andaman. While there are reports of successful production of gas from the Northern Siberian onshore, there is as yet no record of such production from offshore. There are numerous challenges for advances in Science and Technology for the exploitation of such sources. These are described in the article in this volume on the Need for Gas Hydrates Investigation along the Continental Margins of India by Harsh K. Gupta and Kalachand Sain of National Geophysical Research Institute, Hyderabad and in a brief Review by A. Rastogi of Gas Authority of India.

iii) Underground Coal Gasification

The occurrence of coal of low rank lignite at 300-800 metre depth in India has been reported. Mining to bring such a material to surface is not feasible. However, technology for its use for energy has been envisaged through injection of steam and oxygen or air by pipeline, leading to conversion to evolution of gas of a mixture of methane, carbon monoxide, hydrogen and carbon dioxide which can be utilized for electrical power generation. A pilot project in Gujarat has successfully demonstrated the feasibility of such technology. A brief account of the results and the potential was provided by Professor MM Sharma, former President of the Indian National Science Academy at the Ahmedabad Seminar. Further enlargement is necessary to outline fully the larger scale potential.

iv) Renewable Sources

The potential of harnessing natural energy forces for availability for use in several ways from advances in Science and Technology has received considerable attention in India for three decades. These include wind, ocean and the solar sources. The interest in further investment in Science and Technology was confirmed through the establishment of a Commission on Additional Sources of Energy and a Government of India, Ministry of Non-Conventional Energy Sources in 1982. Special incentives have been provided for scientific work and for pilot sources of a larger scale to utilize the thermal heat energy of the sun and to produce electrical power from wind and sunlight. The developments on the Role of Solar Photovoltaics is described in an article by Professor K.L. Chopra in this volume.

Wind farms for generating electrical power to feed into the grid in Kutch in Gujarat and in Tamil Nadu are already functioning. Wind power is intermittent. Highly efficient wind turbines have also been evolved by scientists at the Indian Institute of Science and National Aerospace Laboratories, Bangalore. The Department

of Ocean Development of the Government of India has supported the pilot scale production of energy from ocean waves in the Indian Institute of Technology, Chennai and in the Kerala Coast and this would be enlarged. A major source of energy, utilizing the difference in temperature of the ocean surface and at lower depths, is being pursued by the Ocean Thermal Energy Project in the Chennai offshore by the National Institute of Ocean Technology, Chennai of the Department of Ocean Development and recorded in the Ocean Vision document.

CLEAN ENVIRONMENT

India had clearly committed to the highest environmental quality, nationally and was among the foremost internationally from 1971 Stockholm Conference. This has been translated to active Science and Technology support in many organisations and the National Environmental Engineering Research Institute and the formation of a Ministry of Environment, Forests and Wildlife. The concern for urban clean atmosphere was reflected in 1974 with detailed investigations to ensure clean atmosphere in Agra area with many world heritage monuments including the Taj Mahal. Indian Oil and Gas Industries have continuously improved the quality of fuels by hydro desulphurisation of petroleum gas and liquid oil products. Special attention has been shown for availability of high quality fuels for transport vehicles in major urban cities. The levels of sulphur dioxide and suspended solids have been continuously reduced in the atmosphere during a period of very massive increase in urban population and use of domestic fuels and especially motorised vehicles. Petrol, diesel and Compressed Natural Gas are being made available. There is also widespread use of Liquified Petroleum Gas (LPG) for domestic and urban catering services to replace coke and firewood. Incentives are provided for relocation of industries.

Water sources and supplies have received attention. Reuse of treated city effluents, reduction of dissolved solids by high efficiency membranes are among the results of advances in scientific research.

GLOBAL ATMOSPHERE

India has made substantial contributions towards elimination of all materials identified in the destruction of atmospheric ozone such as chlrofluro hydrocarbons in refrigeration, aerosol, air-conditioning as well as chloromethanes and hydocarbons. Commitments to the Montreal Protocol on Ozone have been fully met through scientific research, technology development and fiscal assistance and legal framework.

India is also committed towards all measures to control global warming through reduction of release of gaseous materials into the atmosphere. These are related to energy consumption. India has accepted adherence to the Kyoto Protocol. The article on Global Warming – Kyoto Protocol and Climate Change by Dr Shyam Lal of

Physical Research Laboratory, Ahmedabad in this volume provides an excellent overview.

MEETING NATIONAL NEEDS OF FOOD

India attached the greatest importance to fully meeting the national needs of Food to every section of the population, and to attain food security for self reliance, poverty elimination and economic growth. Agriculture Research, Technology Development for higher productivity of land, provision of assured irrigation, and ensuring fulfilment of national needs have had the highest priority in all national plans. These concerns have continued. There has been extra-ordinary success in increasing cereal and pulses production in the past fifty years. Other agricultural food commodities such as vegetables, fruits, milk, poultry, meat and fishery aquatic marine organisms have also increased to meet needs and to support growth of export. The Generally Recommended Dietary Allowances prepared by Indian Council of Medical Research service as the guide for providing adequate food from infancy to adultfood and requirement in pregnancy and lactation. The Development Goals and Strategy and Policies of Ninth Plan for 1997-2002 attach the highest importance to meeting National Needs of Food.

Although India has been successful in improving food production during 30 years in a phenomenal way, there are some concerns on future capabilities noting the growth of population, limitations on land and water availability while accepting needs of forest cover. These are reflected in the major study on Prospects for India's Cereal Supply and Demand to 2020 of the International Food Policy Research Institute, Washington D.C. prepared by G S Bhalla and colleagues.

Indian Agricultural Research has resulted in the development of improved high yielding varieties in rice, wheat and other cereals. The conversion of Research output to actual national production requires further measures, in addition to subsidies on fertilisers, power and on committed procurement. India has also had great success in improving yields of vegetables, fruits and extending them to many new areas. Special attention has been possible to arid zones. Sugar production has had a phenomenal increase and there are limitations on exports. India continues to depend on imports of vegetable oils. The potential for marine supply and fish farming are immense and yet to be realised.

Genetic Engineering is a new advance in science and has been applied to develop pest resistant varieties with high yields. There is however no general consensus on the long term benefits of such technology. There are also new worldwide movements against Genetic Engineering, Synthetic Pesticides and Fertilisers.

There are many puzzles in the dilemma of having high stocks of 30 million tonnes of foodgrains in Government organizations and the inability to reach these

to several tens of millions of people who are not receiving minimum nutrition or even energy calories. There are doubts on the total quantum of needs for foodgrains.

These are the basis of the detailed analysis entitled 'Can India Feed itself' by Professor Kirit S. Parikh, Director of the Indira Gandhi Institute of Development Research, Mumbai included in this volume. A number of policy and activitiy measures are outlined to achieve food security in a positive and confident manner. They need reflection and implementation.

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Clean Energy from Coal Gasification for Power Generation

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INTRODUCTION

The Indian Energy and Power Sectors present a mixed picture of hopeful optimism and prohibitive procrastination. While the country's needs are projected to be 1.06 billion kwh by the end of XI Five Year Plan (2011-2012), and while coal, the primary source of power and energy, is available in abundance in the country, a clear plan for coal utilization is not in place. For example, the technology of coal gasification, which was initiated in India in mid Sixties, was shelved until the late Eighties. Even after two of the country's premier institutions, CSIR and BHEL, have joined together to evolve a firm strategy for R&D and commercialization by recommending the establishment of a 45 MW IGCC (Integrated Gasification Combined Cycle) retrofitting demonstration plant at Sabarmati in 1995, Government of India faltered by not making available the allocated funds in the IX Plan. As a result, the debate on the need to establish IGCC for clean energy is continuing endlessly even after Indian scientists started its coal gasification activity four decades before. This paper tries to make yet another attempt to advocate the urgency of establishing the IGCC technology in India by recalling some of the achievements made in this area by IICT-Hyderabad.

EFFICIENT USE OF COAL

The current annual growth in power sector is of the order of 8%. Coal provides the feedstock for more than 70% of power generation in the country and is in abundant supply, and with limited oil and gas supplies, it should be the obvious choice for a greater role in building our economy. It is clear that the use of hydrogen-rich liquid and gaseous fuels like naphtha or LNG only provide a short-term solution to the country's acute power needs, as they add excessive cost burden to the consumer. The recent failure of Enron is a moot point. On the other hand, the continued use of coal in the same inefficient way as in the PC boilers entail high handling losses, large inputs of precious raw-material, increased GHG loading of the atmosphere, avoidable emission of particulates, etc. Development of atomic power too has its limitations in India. Therefore, as indicated in Slide 1, India should focus on the use of clean coal technologies like gasification which not only caters to the energy and power needs of the country but may also provide sufficient justification for even

chemicals production via syngas, carbon oxides and hydrogen. Some of the multiple applications of coal gasification are presented in slide 2.

COAL GASIFICATION

Coal gasification is a term used for describing the process of reacting coal with a mixture of gases such that the internal energy of coal is transferred to product gases without much loss. Steam, oxygen, carbon dioxide and hydrogen are some of the gases that are used. It is an endothermic process and therefore requires a part of the coal to be combusted to provide the heat of the reaction. The process can be carried out under pressure leading to certain advantages in operation as well as utility of the product gases. Pressure gasification is also preferred to atmospheric gasification as it increases the throughput without increasing the equipment size. Slide 3 presents the important coal gasification reactions. Carbon in coal reacts with steam decomposing it into carbon monoxide and hydrogen. This reaction requires absorption of heat. In presence of excess steam the stoichiometry changes somewhat to produce carbon dioxide. In actual practice both oxides of carbon are formed during gasification in sizable quantities. However, the most of the carbon dioxide produced is from the exothermic combustion reaction, which provides the endothermic heat necessary for the carbon-steam reaction. A part of this carbon dioxide is also consumed in a slower gasification reaction with carbon to produce more carbon monoxide. The contacting device, which facilitates these gasification reactions between coal, steam and oxygen to occur is a called gasification reactor or simply gasifier, and the composition of the gas produced depends on both the operating conditions as well as the type of gasifier employed.

DIFFERENT GEOMETRIES OF GASIFIERS

Depending on the application and also characteristics of coal, different geometries of gasifier have evolved over a period of time. Three geometries of gasifiers are important – Moving bed, Fluidized bed and Entrained bed. These are schematically shown in slide 4.

Moving Bed Gasifier

In moving bed gasification, sized coal (25-60mm) is fed from top while the reacting gases rise through the bed from bottom. Coal and gas interact in a counter current way as coal is successively dried, devolatalized gasified and combusted and gas becomes successively richer in hydrogen, carbon monoxide and carbon dioxide. Once coal gets depleted of most of its combustibles, it becomes ash and leaves through a device called grate at the bottom. The maximum temperature reached is of the order of 1100 C. A significant feature of this process is that the grate is made to rotate at a controlled speed so that ash is continuously discharged. The gas rich

in hydrogen leaves at the top along with some suspended particles, which are scrubbed off before further processing.

The moving bed technology is characterized by large residence time for coal with typical residence time being two to three hours. M/s. LURGI, Germany, pioneered this technology. However IICT, Hyderabad and Corporate R&D BHEL, Hyderabad have separately adopted this technology with many variations. The present paper deals with some of the typical studies carried out at IICT.

Fluidized Bed Gasifier

Fluidized bed process of gasification of coal uses small particles (1-6mm) as feed and the gasifying agent as the fluidizing medium itself. Coal is introduced at a convenient position near the bottom of the gasifier, whereas the gasifying medium, which consists of air/oxygen and steam, is introduced slightly below. The bed behaves more or less like a well-mixed reactor with temperatures fairly uniform at about 800-9000 C depending on coal within about +500 C. As coal gets converted into gas, the particles of coal reduce in size and escape along with the product gas. These particles are relatively richer in carbon compared to the moving bed process and are required to be recycled. However, a portion of the ash is also withdrawn as bottom ash.

M/s. WINKLER developed the fluidized technology. In some improved versions of the fluidized bed technology for example in KRW and IGT processes, the gasifying medium is admitted using a single appropriately located vertical pipe within the gasifier causing localized higher temperature which aid in achieving better conversion than the normal fluidized bed. The average residence time in a fluidized bed is 4-6 minutes for coal.

Entrained Bed

The third most important geometry of gasifer is the Entrained Bed in which very fine particles of coal (less than 1mm) are transported through a large chamber in vast stream of air/oxygen and steam. Since the coal particles are very small in size the reactions occur very fast resulting in low residence time of the order in a few seconds. Coal may be admitted as a wet mixture along with water or it may be admitted dry with steam entering the reaction separately.

The TEXACO Gasification process is an example of wet injection of coal, whereas the SHELL process is an example of dry injection of coal. The TEXACO gasifier is more versatile as it can take a wide variety of feedstock including petroleum coke and biomass.

INTEGRATED GASIFICATION COMBINED CYCLE (IGCC)

Integrated Gasification Combined Cycle (IGCC) uses a two-stage generation of power using gas turbine and steam turbine taking of advantage of higher efficiencies possible in gas turbines. The gas coming out of the gasifier is cleaned of particulates, sulphur compounds and any other eroding or corroding substances and is passed through gas turbine. The gas turbine generates roughly two-third of the total power. The hot flue gases from the gas turbine exhaust are sent into a heat recovery steam generator for generating high-pressure steam which is used to run a steam turbine for producing more power. The second stage power is almost one-third of the total power. To complete the integration, the air needed for gasification is abstracted from the gas turbine which adds efficiency to the overall operation making IGCC more efficient compared to a PC boiler by 10-15 percentage points. If the hot gas coming from the gasifier is cleaned without significant drop in temperature so as to match with the turbine entry temperature, the overall efficiency of conversion may be even higher by 2-3 percentage points. A comparison of the performance of IGCC systems vis-à-vis steam cycle is given in slide 5. The particulate emission and other environmental parameters such as SO_x and NO_x emissions are lower in IGCC. Thus, the IGCC technology has a double advantage of higher efficiency and better environmental acceptability.

IICT'S PILOT PLANT STUDIES

In slide 6 the R&D and pilot plant facilities available in India are listed along with some operational history.

IICT has commissioned and operated a 24T/day moving bed coal gasification plant for over a decade since 1983. A summary of IICT's experimental studies is presented in Slide 7.

Seven different coals including lignite were studied processing more than 3,000 tonnes of coal logging a total operation of more than 4,600 hours. The properties of coal that have been used are summarized in slide 8. These coals are typically low-grade Indian coals having ash content 14-35% with calorific value reaching from 4,100–6,400 kcal/kg. The conclusions drawn from these studies are presented in slide 9.

The studies of IICT have conclusively established that the dry ash moving bed system is very suited for low-grade Indian coals with high ash fusion temperature. The gasifier can accept a wide range of coals without any process problems. A comparison of low and high-pressure operations has led to the conclusion that coal gas efficiency, gas calorific value and specific throughput increases with increasing pressure. These studies at IICT were followed by a detailed study of establishing gasification characteristics of one identified low-grade coal from North Karanpura,

which was earmarked for IGCC power generation. The analysis of this feed coal, the composition of gas that was obtained and the efficiency are presented in slide 10.

At this cold gas efficiency, 13 air blown gasifiers are required for a 600 MW IGCC plant.

IGCC FOLLOW-UP

Government of India decided to explore the possibilities of establishing IGCC technologies in India and appointed a committee to make the recommendations. This committee has chosen 4 technologies world wide for possible application to IGCC. They are mentioned in slide 8.

One of the 4 technologies is the IICT developed moving bed dry ash process. Based on the results of IICT studies, a techno-economic feasibility report comparing the above mentioned 4 technologies was prepared and submitted to the Government by IICT (CSIR). Salient feature of this report is that entrained bed processes are not applicable to Indian coals, while fluidized and moving bed processes perform closely.

The capital cost of a 100 MW GEF-assisted demonstration plant is presented in slide 12. The unit cost is Rs. 6.1 crores per MW, which is slightly higher than the cost of the PC plant with FGD. In India the environmental penalties of using coal in low efficiency PC plants are likely to become stringent once the Kyoto protocol comes into operation in 2008, when all industrialized nations are required to reduce their GHG emissions to below 5.2% of their 1992 levels. IICT is ready to offer its expertise in a bid to rid the nation off the energy starvation in a clean and efficient manner using indigenous resources.

ACKNOWLEDGEMENTS

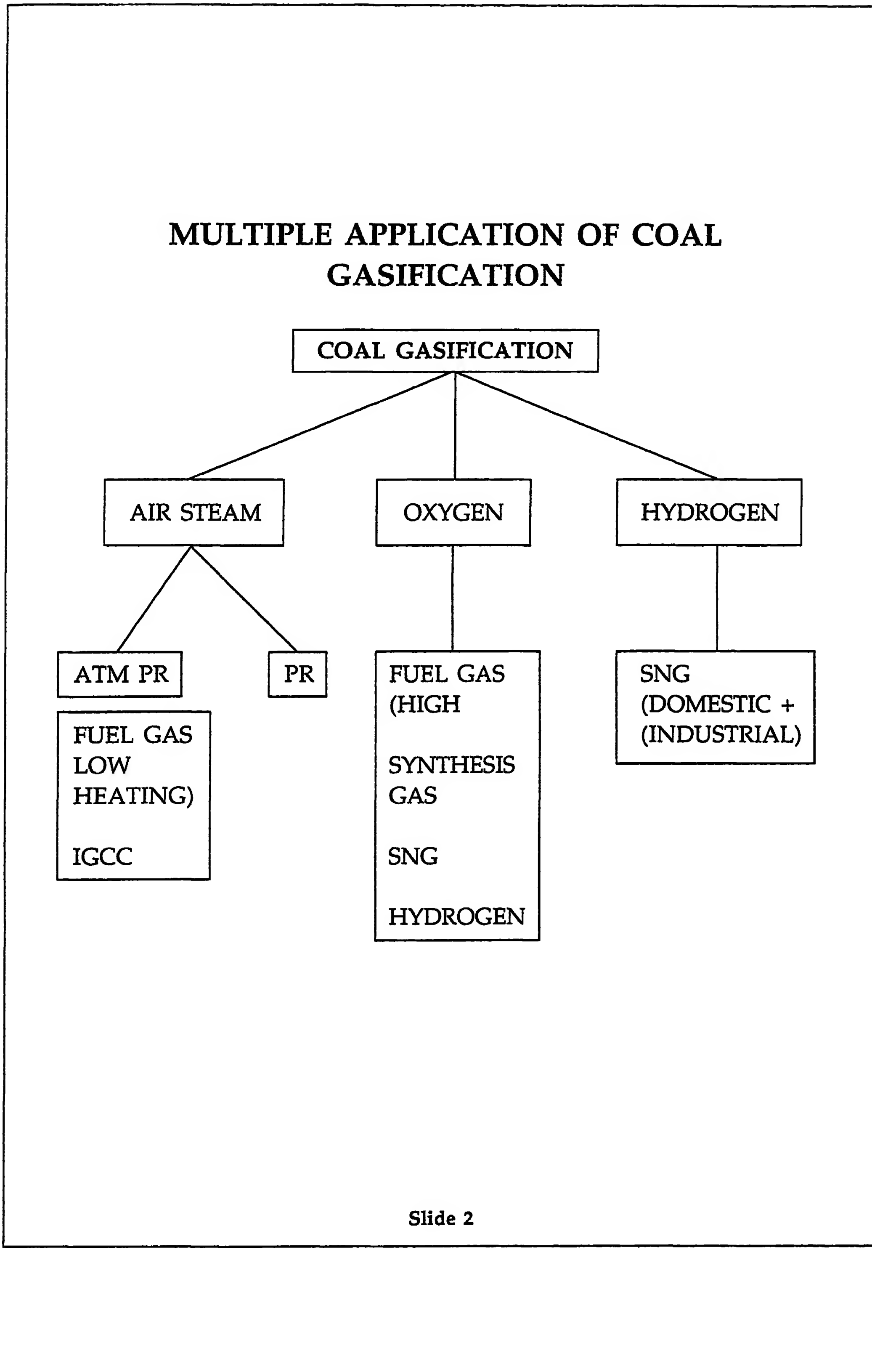
IICT plant performance data and other relevant information for preparing this manuscript are provided by Coal & gas Technology Division, Indian Institute of Chemical Technology, Hyderabad.

EFFICIENCY AND CLEAN USE OF COAL INDIAN SCENERIO

- ANNUAL POWER GROWTH : 8%
- LIMITED OIL AND GAS RESERVES
- WASTAGE OF NAPHTHA FOR POWER GENERATION
- RECENT EFFORTS TO EMPLOY NATURAL GAS FOR POWER GENERATION
- LNG IMPORTS EXPENSIVE
- LARGE DEPOSITS OF HIGH ASH COALS
- EMPHASIS ON COAL FIRED POWER GENERATION
  - HIGH HANDLING LOSSES
  - LOW CONVERSION EFFICIENCY
  - HIGH PARTICULATE EMISSIONS
- LIMITED ATOMIC POWER

INDIA NEED TO PURSUE A POLICY TO PROMOTE EFFICIENT AND CLEAN COAL TECHNOLOGIES THROUGH PREDOMINANTLY INDIAN EFFORTS COUPLED WITH SPECIALIZED INPUTS FROM DEVELOPED COUNTRIES UNDER THE AMBIT OF KYOTO PROTOCOL

Slide 1


MULTIPLE APPLICATION OF COAL GASIFICATION
COAL GASIFICATION
AIR STEAM
OXYGEN
HYDROGEN
ATM PR
PR
FUEL GAS LOW HEATING)
IGCC
FUEL GAS (HIGH
SYNTHESIS GAS
SNG
HYDROGEN
SNG (DOMESTIC + (INDUSTRIAL)
Slide 2

BASIC REACTIONS CONTRIBUTING TO THE HEAT IN THE GASIFICATION PROCESSES

ENDOTHERMIC REACTIONS

$C + H_2O$	$\rightarrow$	$CO + H_2$	$\Delta H = 119$ KJ/mol
$C + CO_2$	$\rightarrow$	$2CO$	$\Delta H = 162$ KJ/mol
$C + 2H_2O$	$\rightarrow$	$CO_2 + 2H_2$	$\Delta H = 16.3$ KJ/mol

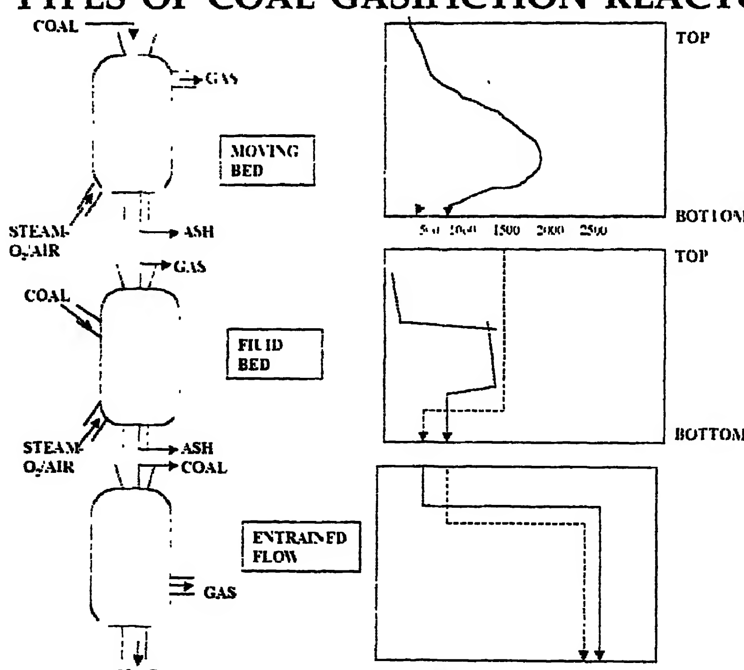
EXOTHERMIC REACTIONS

$C + O_2$	$\rightarrow$	CO_2	$\Delta H = -406$ KJ/mol

THE ART OF GASIFICATION REMAINS IN BALANCING THE EXOTHERMIC AND ENDOTHERMIC REACTIONS AND MAINTAINING THE REACTION TEMPERATURE

Slide 3

TYPES OF COAL GASIFICTION REACTORS



Slide 4

COMPARISON OF IGCC AND STEAM CYCLE (SC)

	IGCC	SC
POWER GENERATION, MW	60	60
EFFICIENCY, %	40	28
HEAT CONSUMPTION, BTU/KW	8,700	13,700
SO_x, TPD	7	8.4
NO_x, ppm	110	200
PARTICULATES, MG/Nm2	21	85
ASH	NONPOLLUTING	POLLUTING
POWER/HEAT	1	0.5
WATER REQUIREMENT, UNIT	1	

Slide 5

NATIONAL STATUS OF R&D IN COAL GASIFICATION/IGCC

PRESSURISED MOVING BED

- 24 TPD GASIFIER AT IICY (CSIR) SINCE 1989.
- EIGHT DIFFERENT COALS INCLUDING LIGNITE HAVE BEEN TESTED.
- 150 TPD GASIFIER AT BHEL (TRICHY) SINCE 1989. DIFFERENT COALS HAVE BEEN TESTED.
- 6.2 MW IGCC (4.0 MW GT AND 2.2 MW ST) BEING OPERATED FOR GENERATING DESIGN DATA FOR HIGHER SIZE UNITS SINCE 1989.

PRESSURISED FLUIDISED BED

- 18 TPD PILOT PLANT BEING OPERATED FOR GENERATING DESIGNDATA AT HYDERABAD BY BHEL SINCE 1990.
- 150 TPD PFBG ADDED FOR OPERATING WITH 6.2 MW IGCC AT BHEL (TRICHY).

Slide 6

IICT—PILOT PLANT STUDIES

— NUMBER OF COALS TESTED : 7

— NUMBER OF CAMPAIGNS : 21

— TOTAL PERIOD OF OPERATION: 4600 HOURS

— TOTAL COAL PROCESSED : 2900 TONNERS

— SINGLE LONGEST RUN: 65 DAYS

COAL	CAMPAIGNS	COAL PROCESSED (T)	PERIOD HRS	
GK	6	460	2015	O_2, AIR
MNG	3	410	505	O_2, AIR
HLP	2	342	460	O_2, AIR
SAM	1	160	150	O_2
SNG	3	300	360	O_2, AIR
NEY	2	150	148	O_2
NKP	4	1075	959	O_2, AIR
	21	2897	4597	

Slide 7

RANGE OF COALS TESTED AT IICY (MGC)

- ASH : 14-35%
- MOISTURE : 4-11%
- VOLATILE MATTER : 25-45%
- FIXED CARBON: 35-46%
- CALORIFIC VALUE kcal/kg : 4100-6400
- ASH FUSION, Temp. °C : 1240-1400

COAL TESTED	CODE
*SAMLA (RENIGUNJ)	SAM
*HINDUSTANLALPETH	HALP
*SINGRAULI	SING
*MANUGURU	MNG
*GODAVARI KHANI	GK
*NORTH KARANPURA	NKP
*NEYVELI LIGNITE	NEY

Slide 8

CONCLUSIONS OF IICT STUDIES

*IN DRY ASH MOVING BED SYSTEM

*High ash low grade, non-coking Indian coals with high ash fusion temperature can be gasified easily.

*The gasifier can accept wide range of ash content without any process problems.

*Pressure operation improves the process performance with regard to

—cold gas efficiency

—gas composition

—c.v. of the gas

—specific gas throughput and

—carbon conversion

*449 t/h of candidate coal is required to generate a net power of 586 MW with 13 air-blown gasifiers.

AIR-STEAM GASIFICATION OF NORTH KARANPURA COAL AT 10 kg/cm^2

ANALYSIS OF FEED COAL	
Proximate analysis, wt%	
Moisture	5.6
Ash	36.2
Volatile matter	25.3
Fixed Carbon	32.0
Calorific value, kcal/kg	4105
COMPOSITION OF THE GAS, VOL%	
Pressure, kg/cm2	13.8
Hydrogen	20.7
Carbon dioxide	15.4
Nitrogen	45.5
Hydrogen sulphide	0.13
Moisture	0.8
EFFICIENCIES	
Cold gas efficiency %	74.06
Carbon conversion%	86.32
Steam decomposition%	58.22

Slide 10

GASIFICATION TECHNOLOGIES SELECTED FOR EVALUATION IN INDIA

I. IICT Developed Moving Bed (Dry Ash) Process

II. KRW Ash Agglomerating Process

III. Shell Dry Entrained Bed Process

IV. Texaco-Slurry Fed Entrained Bed Process

Slide 11

PROPOSED 100 MW NTPC DEMO PLANT (IGCC) AT DADRI

FINANCIAL PLAN	
CAPITAL COST	Rs. 575 Crores* (*with import duty exemption)
IDC	Rs. 35 Crores
TOTAL PROJECT COST	Rs. 610 Crores

BREAK UP	
Equity contribution from NTPC/MSEB	Rs. 100 Crores (16.4%)
TDB Loan@60% interest	Rs. 10 Crores (16.4%)
GEF Grant	Rs. 246 Crores (@Rs. 42/$) (40.2%)
CO-FINANCING	Rs. 164 Crores (@Rs. 42/$) (26.8%)
Total	Rs. 610 Crores (100%)

LEVELLISED COST OF ELECTRICITY : 2.36/kwB
COE FOR PC : rs. 2.96/kwh

Slide 12

Integrated Gasification Combined Cycle (IGCC) Development in BHEL

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Corporate R&D Division, Vikasnagar, Hyderabad

INTRODUCTION

Clean Coal Technology can be differentiated from other environmentally acceptable power generating systems because in the former, the process itself produces less pollutants. In other thermal power generating systems, pre or post combustion cleaning is basically retrofit to the combustion process. As a bonus, most of the power generation processed based on clean coal technology also result in higher overall energy efficiency in comparison to PC plants even with supercritical steam parameters. Thus, a dual purpose of containing environmental pollution and release of green house gas (CO_2) is achieved in using clean coal technology.

BHEL, recognizing the importance of clean coal technology, has adopted multifaceted development strategies through the development of PFBC and IGCC for near term application and MHD and Fuel Cells for the long-term prospects.

Of the two near term clean coal technologies being developed concurrently, in PFBC area, in-house development of pressurized fluidized bed combustor and Hot Gas Clean-up system have been completed at pilot scale level, Granular bed filter has been the choice of BHEL for particulate cleaning since this system, with suitable modifications, has the potential for capturing SO_2/H_2S. IGCC has been selected for near term commercial application.

IGCC is characterized by its potential to generate power at higher efficiency due to the possibility of coupling newer generation gas turbines with higher turbine entry temperature (TET). Further the process scheme provides for control of gaseous and solid pollutants generation. Relative emission of SO_x, NO_x and particulate from PC, PC + FGD, IGCC and PFBC based power plants is shown in Fig 1. IGCC stands out as the least polluting amongst coal based power generation.

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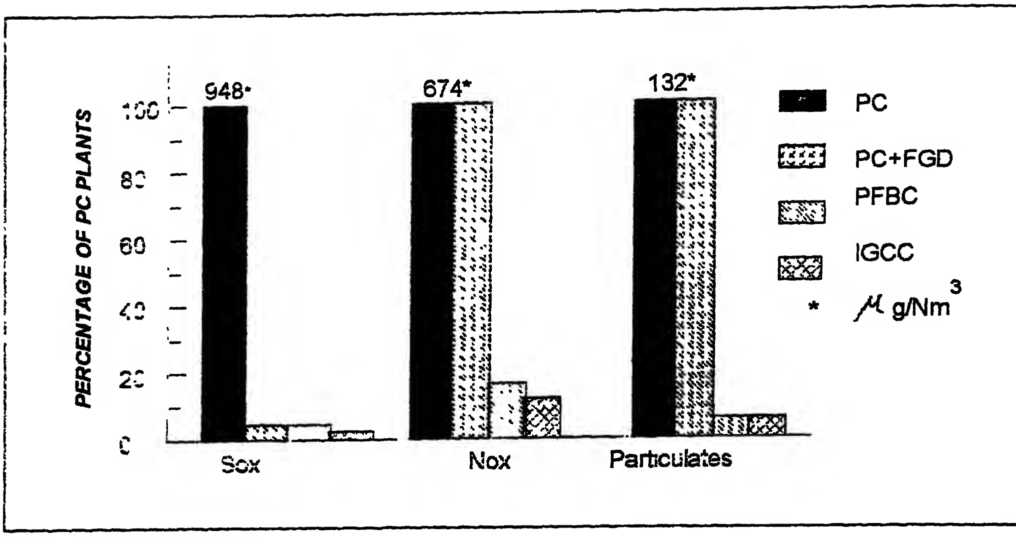


Fig. 1. Relative Emissions

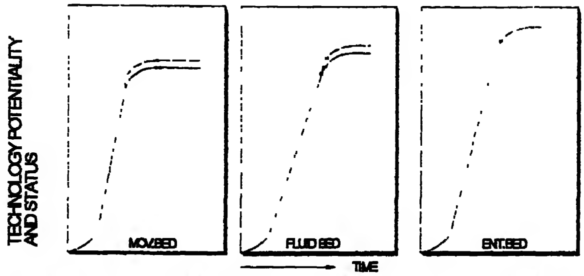
SELECTION OF GASIFICATION PROCESSES FOR IGCC

Selection of gasification process depends on the quantity of ash content and characteristics of the coal. The choice is limited to the three basic gasification processes viz.

- Pressurized moving bed
- Pressurized fluidized bed
- Pressurized entrained bed and their variations

They differ in the method of contact between coal and the gasification media (air-steam or oxygen-steam) and the operating temperature regime. Ash is removed as dry or as slag in moving bed, dry or as agglomerates in fluidized bed and as slag in entrained bed. Coal is fed in dry form in moving bed and fluidized bed and dry or slurry forms in entrained bed gasifier. The coal size that can be usefully reacted also depends on the type of basic process employed, composition of coal mineral matter and its behaviour under gasification conditions. These factors matter in selecting the basic variant of gasification process. Fig. 2 shows a broad comparison of various gasification processes currently in use either in pilot scale or commercial scale.

In addition, the criteria for selection of gasification for IGCC also require close integration of fuel gas generation with gaseous reactant such as air supply from the gas turbine compressor and steam from the heat recovery steam generator. Any mismatch in this closed loop could adversely affect the efficiency or the off-design performance of the IGCC. There is also a conflicting matching requirement between the gasifier and the system heat energy optimization.



COAL FLOW:	COAL MOVE DOWN ON A GRATE	COAL CIRCULATE IN A BUBBLING BED	COAL PROGRESSIVELY ACCELARATE
CONTACT WITH GASIFICATION MEDIA:	COUNTER CURRENT	BACK MIXED	COCURRENT
PERFORMANCE:			
COAL THROUGHPUT TM^2 HR	4.4-6.6	10.0-13.3	13.3-20.0
GAS OUTPUT GJ/M^2 HR	120	158-211	257-281
RAW COAL UTILIZATION	70%	90%	95%
EFFLUENT:	TAR, LIQR, ASH/SLAG	DRY ASH/ AGGLOMERATES	SLAG

Fig. 2. Gasification Processes-Comparison.

Moving bed and entrained flow processes have fairly reached maturity of development, thanks to their application for production of chemical feed stock through oxygen-steam Gasification. Fluidized bed gasification, particularly for coal, is still to be proved in commercial scale.

Indian coals, used in power sector, have low to medium caking and swelling properties but with high ash content of more than forty percent. The ash fusion temperature is generally around 1400 °C. Ash content and characteristics of Indian coals preclude oxygen-blown slagging gasification owing to loss of useful energy of coal in melting large amount of ash. Therefore, for such coals the choice is restricted between moving bed and fluidized bed with dry ash removal.

Fuel gas quality is improved by reducing CO_2 and N_2. Since oxygen-blown gasifiers would be uneconomical for most of the Indian coals, air-blown high temperature fluidized bed, wherein, some CO_2 percentage is reduced by its conversion to CO in Boudurad reaction is more promising. Further, moving bed gasifier uses 5-30mm sized coal compared to 0-6mm in fluidized bed gasifier. This increases raw coal utilization in the latter process. Also, transient load following is faster fluidized bed.

Liquid effluent like tar, wash liquor containing phenols and other organic compound are unavoidable in moving bed gasification process. Their storage, treatment and disposal constitute part of the capital investment and operating expenses. In contrast, fluidized bed produces dry solids, which can be easily stored in silos and disposed off at a fraction of cost of liquid effluent treatment.

For various fuels, BHEL's assessments of appropriate gasification processes are shown in Table 1.

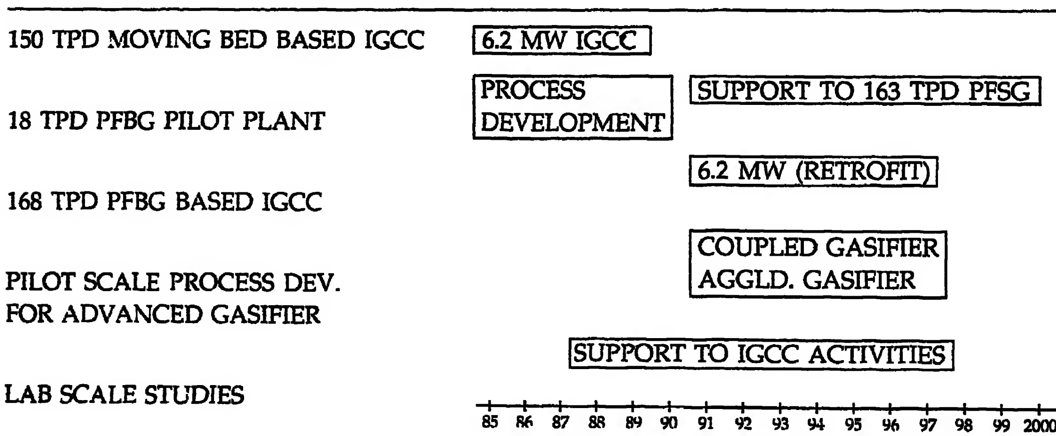
Table I. Gasification Technology Options for IGCC

1. High ash subbituminous coal	:	Non Agglomerating fluidized bed
2. Imported Low rank coal	:	Agglomerating fluidized bed or entrained bed
3. Petrocoke and refinery residue	:	Entrained bed (Dry Feed for higher efficiency, slagging slurry feed with lower efficiency, slagging)
4. Lignite (Predried) (Wet)	: :	Fluidized bed Drying and gasification (DGCC)

BHEL'S IGCC PROGRAMME

A three-tier gasification and IGCC technology development programme was taken up by BHEL. The first phase of development was concentrated on the study of behaviour of a gasifier integrated in an IGCC plant using the then state-of-the art moving bed gasifier with wet gas clean up. This was followed by development of Pressurized Fluidized Bed Gasification (PFBG) technology at pilot scale for different high ash coal feedstocks. The third phase of development was integration of a fluidized bed gasifier (demoplant) with improved energy conversion with the IGCC. Table development phase and the time span are shown in Table-II.

Table II. IGCC Development Programme



IGCC WITH MOVING BED GASIFIER

A 6.2MWe coal based IGCC plant comprising a 4.0MWe gas turbine (GT), a 2.2 MWe steam turbine and a pressurized moving bed coal gasification plant of 150 TPD nominal coal throughput was installed at BHEL's Tricky and was fully commissioned in 1988. The coal gasification plant, developed in-house, consisted of a 2.7m ID x 14m high jacketed gasifier. Crushed coal of 5-30mm size with about 35% ash content was the design feedstock. Gasification media (air and steam) was addmitted through a slowly revolving grate which also aided ash discharge. A good part of the gasification steam was generated in the jacket. A gas cooler was used to recover part of the sensible heat of the raw gas to superheat steam from HRSG. The partially cooled gas was first quenched with recirculating tar oil to capture tar in the gas and was then scrubbed with recirculating liquor in two venturi scrubbers in series to remove particulate matter before admitting to gas turbine. The gas cleaning system adopted in this plant was simpler and different from that in other moving bed gasification processes. Fig. 3 shows the process scheme of the 6.2MWe IGCC plant.

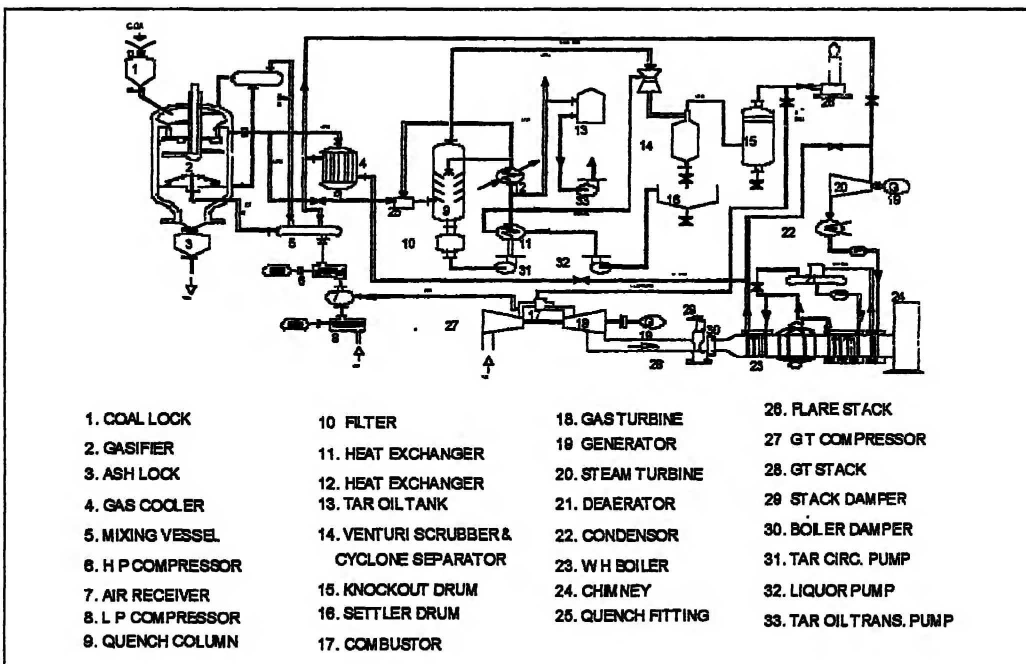


Fig. 3. Schematic of 6.2 MWe IGCC with moving bed.

This plant was operated for more than 5500 hours using mostly Singareni coal with ash content of 27-35% as the base feed stock. About 0.5 million units of power was exported to TNEB Grid.

Under a joint programme, sponsored by the Department of Coal, Govt. of India, North Karanpura coal with 38-40% ash content was successfully tested for

about 30 days each both in BHEL's and IICT's moving bed gasifier under identical pressure and in air-steam gasification mode to generate data for further scale-up. The larger size BHEL gasifier yielded gas with slightly higher calorific value and required less steam.

A mathematical model of movingbed gasifier was developed and validated. The validated model predictions also agreed closely with the performance of BHEL's as well as IICT's moving bed gasifier indicating the applicability of model to different sizes of moving bed gasifiers. The comparison of model prediction and plant data is given in Tables III and IV respectively for BHEL's and IICT gasifier's.

Table III. Comparison of BHEL's Moving Bed Gasifier
Coal: North Karanpura
HCV of Coal 16.98 MJ/kg

Sl. No.	Parameter		I Model	I Plant	II Model	II Plant	III Model	III Plant
1.	Pressure	Mpa	10.8	10.8	10.8	10.8	10.8	10.8
2.	Reactant ratios	kg/kg						
	Steam/Air		0.45	0.45	0.50	0.50	0.56	0.56
	Steam/Coal	0.56	0.56	0.56	0.64	0.64	0.76	0.76
	Air/Coal		1.24	1.24	1.28	1.28	1.36	1.36
3.	Dry Gas Output	NM^2/kg Coal	939	935	1031	1052	1007	998
4.	Specific Gas Yield	Nm^3/kg Coal	2.0	2.0	2.0	2.0	2.1	2.0
5.	HCV of Gas	MJ/Nm^3	6.9	6.71	6.68	6.43	6.31	6.26
6.	Cold Gas Efficiency	%	81	79	77	76	76	75
7.	Cold Conversion	%						6.26
	Total		95	86	91	94	92	93
	Excluding Tar		88	79	84	87	85	93
8.	Steam Decomposition	%	54	51	45	43	38	38

Table IV. Comparison of HCT Moving Bed Gasifier Performance with BHEL's Model
Coal: North Karanpura

Sl. No.	Parameter		I BHEL's Model	I HCT Plant	II BHEL's Model	II HCT Plant
1.	Pressure	Mpa	1.08	1.08	1.08	1.08
2.	Reactant Ratios	kg/kg				
	Steam/Air		0.45	0.45	0.54	0.54
	Steam/Coal		0.82	0.82	0.91	0.91
	Air/Coal		1.81	1.81	1.68	1.68
3.	Dry Gas Output	Nm^3/kg^2h	1163	1174	1231	1286
4.	SpecificGas Yield	Nm^3/kg Coal	2.3	2.3	2.1	2.2
5.	HCV of Gas	MJ/Nm^3	5.48	5.23	5.39	5.20
6.	HCV of Coal	MJ/kg	17.84	17.84	17.00	17.00
7.	Cold Gas Efficiency	%	70	68	68	68
8.	Carbon Conversion	%	88	83	85	88
9.	Steam Decomposition	%	28	32	26	30

PFBG DEVELOPMENT

Pilot scale development of PFBG process for high ash Indian coals was started as a second phase. The pilot scale gasifier consisted of a two-diameter refractory lined pressure vessel with 450mm ID at the bed zone increasing to 750mm ID at the free board. The plant, with max capacity to gasify 18 tonns of coal per day with air and steam at a pressure of 1.08Mpa has been installed at BHEL (R&D) Coal Research Facility at Hyderabad.

Coals with ash content ranging from 35% to 45% were gasified in the temperature range of 1200-1270 K. The plant was operated for 2200hrs including 250hrs of continuous operation.

Fig. 4 shows the schematic of the PFBG pilot plant and Table V gives the summary of the results achieved in the pilot plant with different coals.

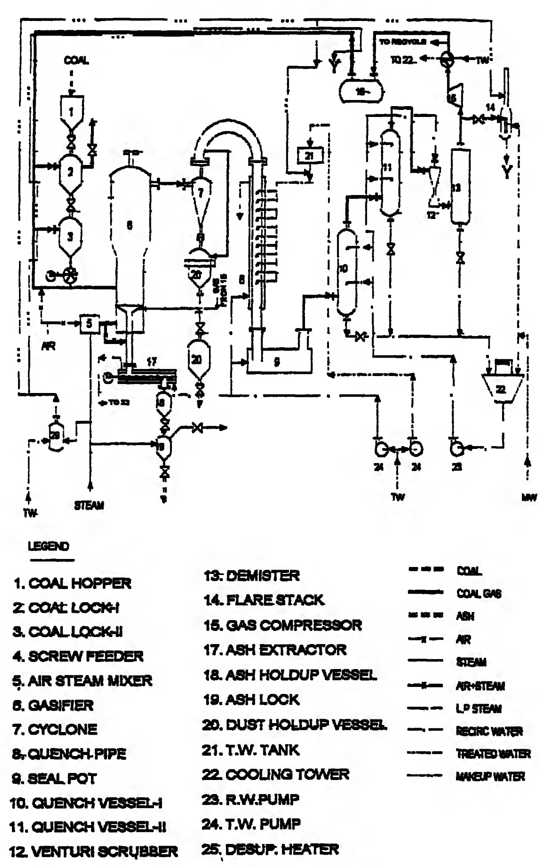


Fig. 4. PFBG Pilot plant process flow diagram.

Table V. PFBG Pilot Plant Performance

Coals			
Rank	–	Subbituminous	
Ash	–	35-45% by wt.	
Mine	–	Singareni, India	
Operating Conditions			
Bed Temperature		K	1223-1300
Gasiffier Pressure		Mpa	UPTO 5.9
Air/Coal		kg/kg	2.0-2.5
Steam/Coal		kg/kg	0.1-0.25
Performance			
Carbon Conversion		%	75-85
Cold Gas Efficiency		%	50-65
LCV of Gas		MJ/kg	3.35-3.75
Steam Decomposition		%	50-60

PFBG DEMONSTRATION PLANT

Further to the completion of pilot plant studies, a PFBG demo plant of capacity 168-tons/day coal throughput has been retrofitted to the 6.2MWe IGCC plant at BHEL's Trichy unit. Being a retrofit, the plant has been sized for a coal gas throughput matched to the gas turbine, and the maximum volumetric capacity of the wet gas clean-up system.

The fluidized bed gasifier is a scaled-up version and essentially having the same geometric configuration and features of the PFBG pilot plant. The gasifier is a refractory lined reactor with 1.4m ID at the bed zone expanding to 2.0m ID at the free board. It is designed to gasify coal with 42% ash content at 1273 K at a pressure of 1.27Mpa to generate coal gas with a net calorific value of 4.0 MJ/Nm^3. The design specific gas yield is 2.45Nm^3/kg of coal. Three refractory lined cyclones operating in series are employed for primary particulate removal. The plant has provision to effect recycle of fines collected in the first two cyclones back to the Gasifier. Coal feeding arrangement is similar to that in the pilot plant. Bottom ash is withdrawn through a cooler and rotary extractor and discharged periodically through a lock system. A heat recovery boiler installed after the cyclones cools the gas to 800 K and generates saturated steam at 2Mpa. This steam along with steam from HRSG is superheated in the existing gas cooler. A portion of the steam is diverted to supply the process steam for gasification and the balance is available for power generation. After cooling the gas is quenched and cleaned of particulate matter in the existing wet clean-up system. A part of the clean gas is pressure boosted for uses in recycle of fines and lock pressurization. Schematic of the PFBG Demo plant retrofit of 6.2MWe IGCC is shown in Fig. 5.

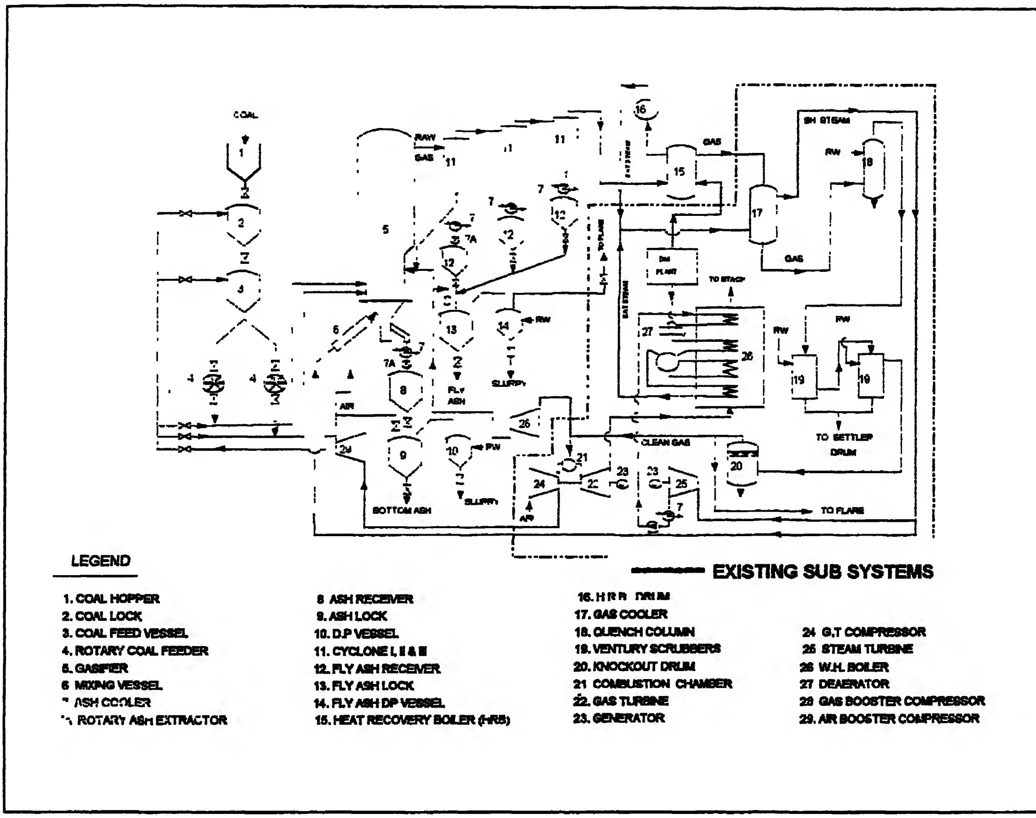


Fig. 5. Schematic of Demoplant Retrofit

The PFBG demo plant project was partly funded by USAID under FACER Programme, Pittsburgh Energy Technology Centre (PETC) and Indian Institute of Technology) Chennai) participated as co-sponsors. This plant has logged cumulative of 1180 hrs. The performance with regard togas composition is equal to and surpassed the design value of 3.7 MJ/NM^3. The performance is shown in Table VI.

Table VI. Performance of PFBG Demo Plant

Total operation	:	1180 HRS
Gas calorific value, (LHV) MJ/Nm^3	:	3.9-4.5
Continuous run (at lower pressure)	:	84 HRS
Max. power output	:	3.6 MWe
Units of Electricity Exported	:	18200

FUTURE PROGRAMME

Complementary to the gasification technology development and operation of 6.2 MWe IGCC both with moving bed and fluidized bed gasification plants, BHEL has gained considerable experience in engineering, erection and operation of IGCC making it the pioneer in India in all aspects of IGCC. In going from pilot scale to demo plant

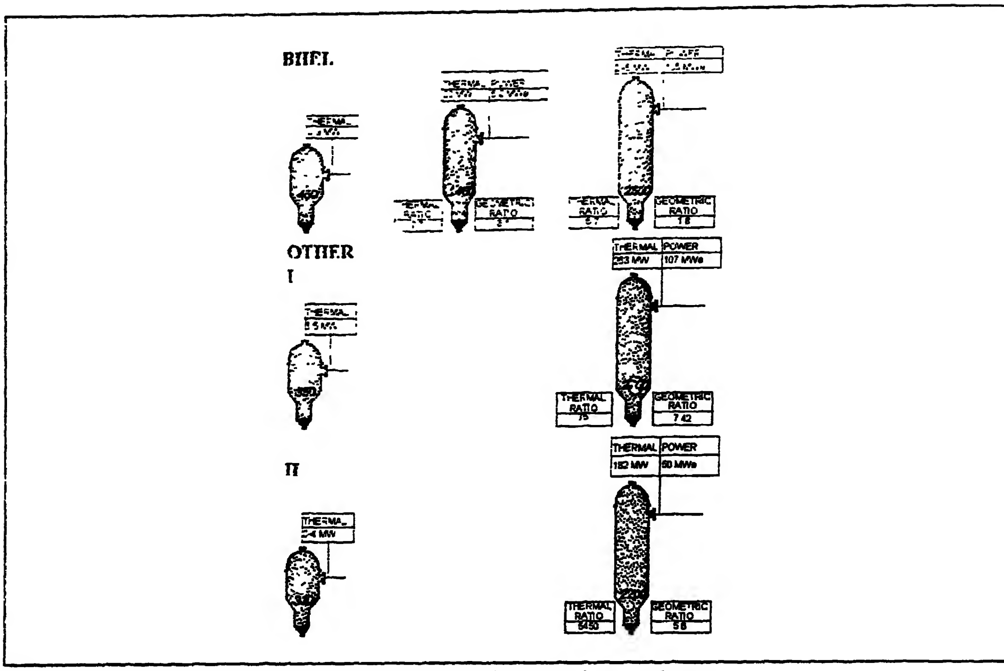


Fig. 6. Comparison of Scale up criteria followed by BHEL & others.

and in further scale-up a conservative approach has been adopted. A comparison of scale-up range adopted by BHEL and other developers is shown in Fig. 6. BHEL is following stepwise scale-up after testing each scaled up version. Thus the success of PFBG demo plant has given the confidence to scale-up to 2.5-2.8m dia gasifier. However, the subsystems design will be new and selection of sub systems will be from the state-of-the art equipment availability. BHEL has the requisite expertise to take up engineering, erection and commissioning of 100MW coal based IGCC on its own or with the need based assistance of a consulting agency.

DEVELOPMENT STUDIES IN FUTURISTIC GASIFICATION

Carbon conversion in PFBG with dry ashremoval using high ash Indian coals is expected to be between 85-90%. For further improvement of carbon conversion, BHEL has taken up experimental studies on coupled gasifier and agglomerating gasification. In coupled gasifier a bubbling fluidized bed combustor operates in tandem with the gasifier. The process air is apportioned between gasifier and combustor. Flue gases from the combustor pass through the gasifier transferring heat and participate in the gasification reaction. The coupled gasifier pilot plant consists of a gasification reactor of 200mm ID single diameter construction and a 100mm ID combustor at the bottom. The design is based on the hydrodynamic coupling criteria established in a cold model.

The agglomerating gasification test rig consists of 100mm ID refractory lined section and a spouting nozzle at the bottom. Part of the process air is introduced through nozzles in the conical distributor. Ash discharge is controlled through adjustment of spout velocity. It was found possible to reduce the carbon content in the discharged ash to less then 2%. Agglomerates population in the discharged ash upto 12% was seen within the gasification of high ash coals using air partially enriched with oxygen. Microscopic examination of the agglomerates showed distinct surface binding. Further work is planned.

CONCLUSION

Through the various gasification developments for Indian coals and operation of 6.2 MWe IGCC plant, BHEL has gained considerable experience in engineering, erection and operation of both moving bed and fluidized bed gasifier's and their integration with IGCC scheme. On the strength of the above. BHEL also successfully bagged and executed an engineerng consultancy export contract valued Rs.6.3 mllons for the design and engineering of Fluidized bed gasfer cum combustor plot plant facility for ESKOM South Africa. BHEL can confidently take up execution of 100-120MW coal based IGCC projects of capacity 100-121MWe.

Need for Gas-hydrates Investigation along the Continental Margins of India

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Gas-hydrates are crystalline form of water and methane molecules that form at high pressure and moderately cooled temperature. The study of gas-hydrates is very important both scientifically and economically because of their widespread occurrences in most of the world's oceans and permafrost regions, and their significant implications on potential energy resources, climate change, drilling hazard etc. Several controlling factors favor formation of large quantity of gas-hydrates in the huge area of Indian continental margins. Therefore, identification and quantification of gas-hydrates are very essential to evaluate the resource potential and hazard assessment in the offshore regions of India. Traveltime tomography of ocean bottom and/or multi-channel seismic data is an important tool to demarcate the zones of gas-hydrates and/or 'free-gas' bearing sediments and their lateral extension thus helps to locate the prospective areas. Whereas waveform inversion is a sophisticated technique to delineate very accurate velocity structure of hydrated sediments and/or 'free-gas' bearing strata, velocities of which can be translated in terms of concentration of hydrates and/or 'free-gas', thus helps for resource assessment. Utilization of natural gas from the gas-hydrates and 'free-gas' lying below the hydrated sediments will significantly improve the overwhelming demand of energy for our country.

INTRODUCTION

Gas-hydrates are ice-like crystals in which gases (mainly methane) are trapped within a framework of hydrogen bonded water molecules (Fig. 1), and occur in two distinct regions of (i) permafrost areas and (ii) submarine sediments of outer continental margins (Sloan, 1998; Kvenvolden, 1998). They are formed at elevated pressure and low temperature in the shallow sediments of outer continental margins when gas concentration exceeds the solubility limit. Fig. 2 displays the phase diagram for gas-hydrate stability field in which the solid line represents the methane hydrate phase curve with the pressure converted to depth assuming hydrostatic conditions in both water and sediments. The dashed line represents the thermal gradient as a function of depth. The figure shows the zone lying within few hundred meters below the seabed where gas-hydrates are stable and water column is more than few hundred

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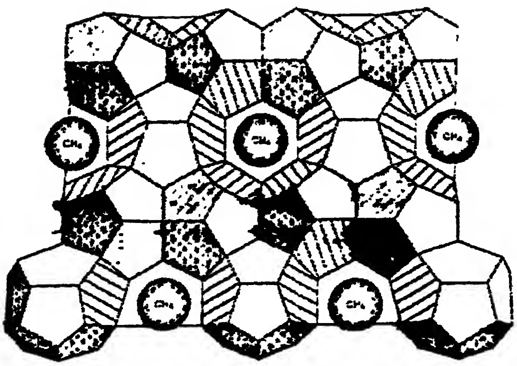

Fig. 1. Gas-hydrates structure in which methane molecules reside in cages of hydrogenbonded water molecules (Kvenvolden, 1998).

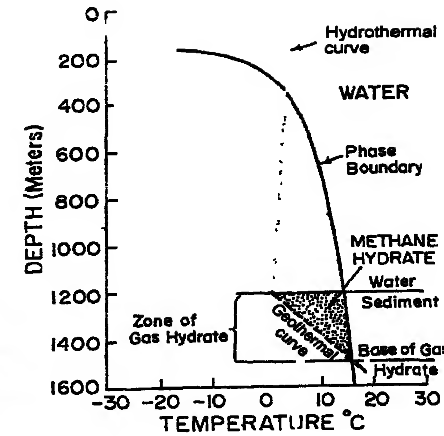

Fig. 2. Phase diagram for submarine gas-hydrates stability field (Sloan, 1990).

meters to maintain thermo-barometric stability conditions for hydrates to exist. Associated with the base of gas-hydrates stability field is the bottom simulating reflector (BSR), which acts as a marker for the detection of gas-hydrates and can be efficiently mapped by seismic experiment. The BSR can be recognized based on certain characteristic features like (i) mimicking the seabed reflection, (ii) high amplitude opposite polarity event w.r.t. seabed reflection, (iii) cutting across underlying dipping strata and (iv) blanking above the BSR.

Occurrences of gas-hydrates in the submarine sediments of outer continental margins have been established from drilling samples at many places in the world. (Henriet and Mienert, 1998; Ginsburg and Soloviev, 1998). Special mention can be made to the Blake Ridge area in the Atlantic Ocean of US continental margin and the Nankai Trough of the Japan continental margin. An inventory of global occurrences shows 77 places in which the presence of gas-hydrates is inferred by geophysical, geological, and geochemical methods. This inventory includes 19 places where samples of gas-hydrates have actually been recovered (Paul and Dillon, 2001). It is estimated that the total organic carbon contained in gas-hydrates is double the amount of total fossil fuel reserves in the world, and one volume of gas-hydrates releases ~164 volume of methane at normal temperature and pressure (Kvenvolden, 1993). Gas-hydrates, by cementing the sediments in which they lie, also act as cap rocks for trapping 'free-gas' underneath. So gas-hydrates are considered as major future energy resources. Therefore, identification and quantitative assessment of gas-hydrates and/or 'free-gas' are very much required to evaluate the resource

potential. Gas-hydrates have other important implications on (a) environmental hazard (methane being the greenhouse gas), (b) geo-hazard (slope failure or instability beneath drilling platforms), (c) heat flow or geothermal modeling etc.

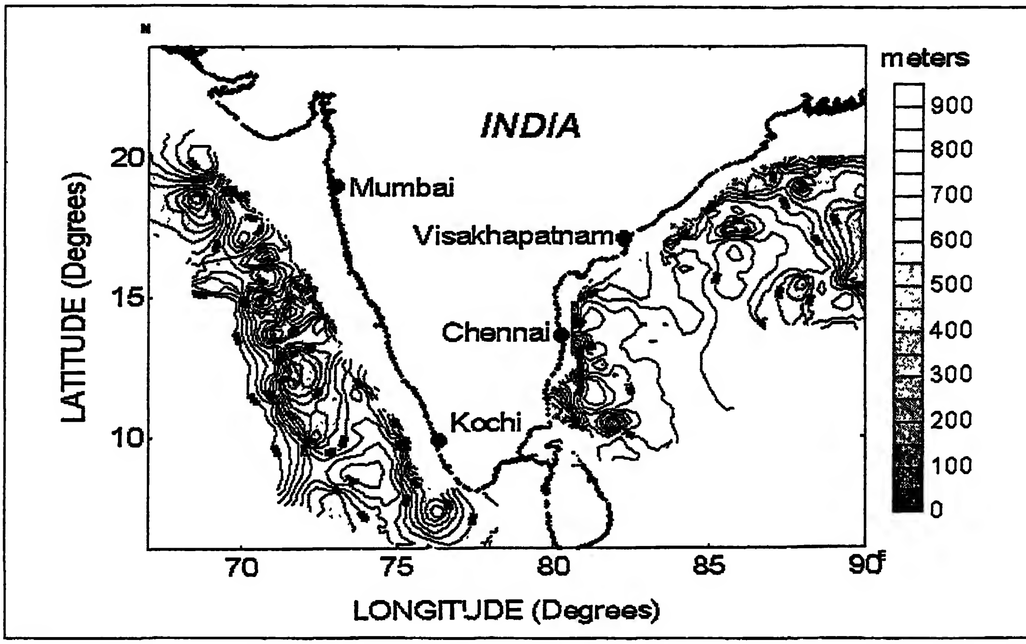

Fig. 3. Variation of thickness of gas-hydrates stability zone in offshore regions of India (Rao *et al.*, 1998)

Pure hydrates have much higher seismic velocities compared to that of normal oceanic sediments within the zone of stability field. Hence, presence of hydrates increases the seismic velocity that again depends on the concentration and distribution of hydrates in the sedir. nts, whereas 'free-gas' lying below the hydrated sediments decreases the seismic velocity considerably. So the velocity variation across a BSR provides useful information for demarcating the zones of gas-hydrates and /or 'free-gas' bearing sediments. The velocity increases and/or drops across the BSR against the background velocity trend can be translated in terms of concentration of hydrates and/or 'free-gas'. Therefore, estimation of very accurate seismic velocity is a must for evaluating the true potential of gas-hydrates.

However, quantitative assessment of gas-hydrates has remained elusive due to lack of precise relationship between seismic velocities and hydrate content and non-stability of gas-hydrates at normal pressure and temperature. The way hydrates fill the pore spaces of sediments is also not well established. Research efforts are on throughout the world to understand the nature of distribution and formation mechanism of gas-hydrates with a view to quantitative assessment of gas-hydrates.

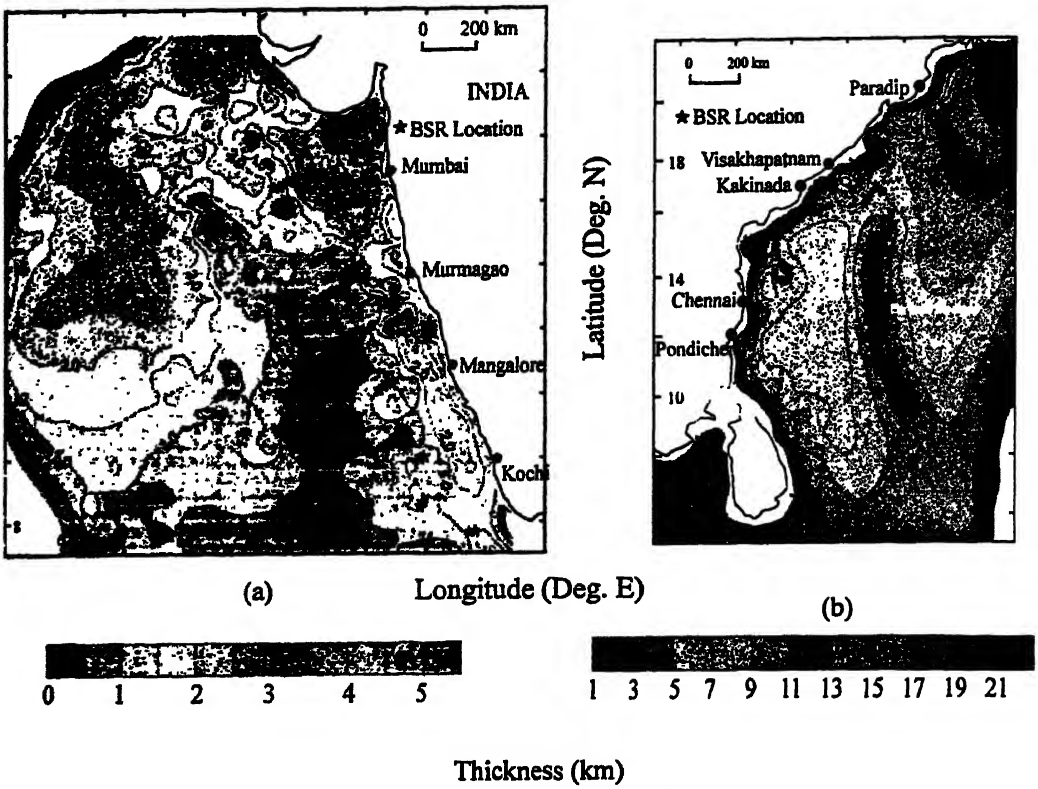

Fig. 4. Map showing sediment thickness distribution and BSR locations in (a) western offshore an (b) eastern offshore of India (Gupta *et al.*, 1998).

PROSPECTS AND INDIAN INITIATIVES

Various controlling factors such as bathymetry, seabed temperature, sedimentar thickness, rate of sedimentation, organic carbon content etc. indicate favourabl conditions for the formation of gas-hydrates in the vast area of Indian continenta margins. Using these parameters, NGRI (Rao et al., 1998) has prepared a map (Fig.3 of gas-hydrate stability zone for both offshore regions of India that serves as a deptl window for mapping BSR or gas-hydrates. Upon scrutinizing more than 50,000 line km of single channel analog seismic data, NGRI (Gupta et al., 1998) has also identifie probable locations of BSR (Fig.4) in both offshore regions of India. More detaile information about the identification and quantification of gas-hydrates can be obtaine from the analysis of large offset multichannel and/or wide-angle seismic data Recently, Sain *et al.* (2000) have analyzed a small segment of multichannel seismi data in the Makran accretionary prism in the Arabian Sea utilizing the advance

seismic data processing software and have produced a clear structural image of BSR with its areal extent (Fig. 5(b)). Application of more sophisticated full-waveform inversion at two CDP locations viz. CDPs 4375 and 4400 has provided accurate velocity variation across the BSR (Fig. 5(a)). The inversion results reveal a thick layer of 'free-gas' (~ 200-350m) zone underlain by ~ 160m thick hydrated sediments, only comparable to the sonic log results (Fig.5(c) of ODP leg 164 at Blake Ridge sites of 995 and 997 (Holbrook *et al.*, 1996).

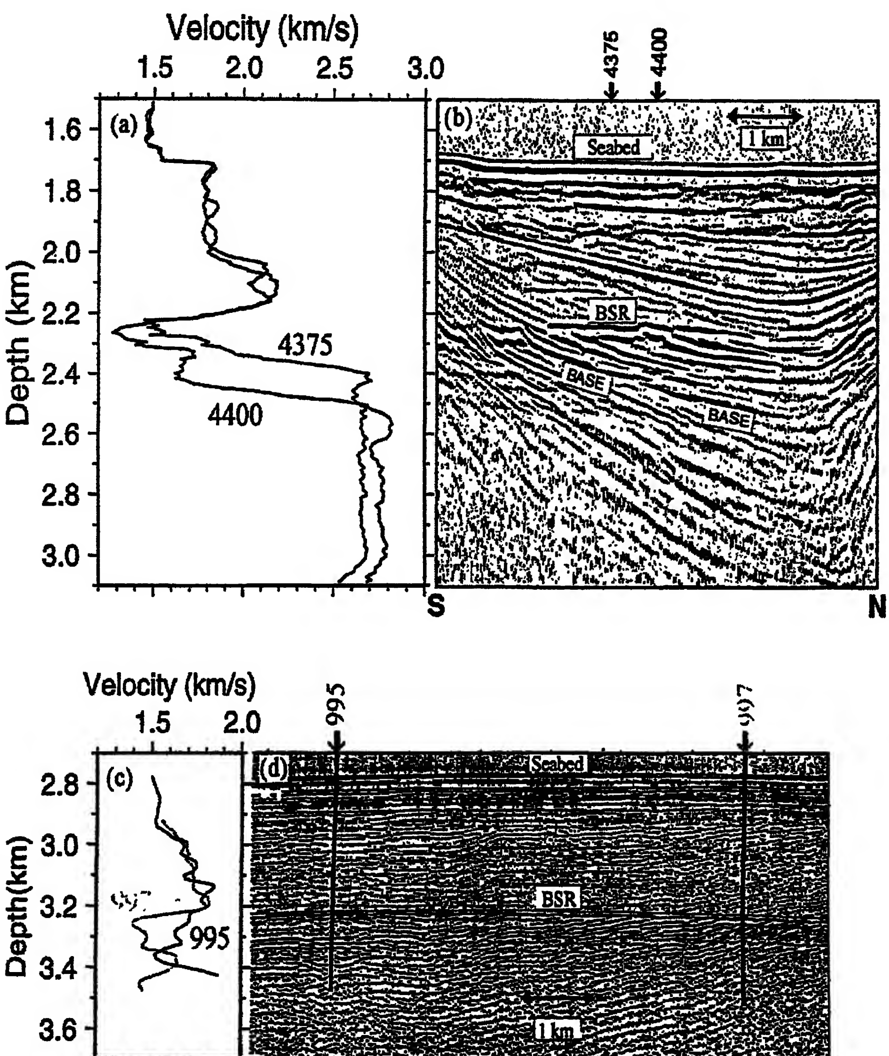

Fig. 5. (a) Waveform inversion results at CDPS 4375 and 4400, (b) Seismic section for the Makran accretionary prism (Sain *et al.*, 2000), (c) Sonic log results at sites 995 and 997 of ODP leg 164, and (d) Seismic section in the Blake ridge area (Holbrook *et al.*, 1996).

FUTURE STRATEGY

Using the advanced seismic data processing software, clear structural image of BSR can be constructed without any reliable velocity information. It is the sophisticated waveform inversion that provides very accurate seismic velocity structure including the delineation of thin layers. But quantification of gas-hydrates and 'free-gas' has remained elusive due to lack of precise relationship between seismic velocities and saturation of gas-hydrates and 'free-gas'. A three-phase semi-empirical time average equation is mostly used for quantitative assessment of gas-hydrates. However, this cannot take into account the effects of sediment microstructure and anisotropy that are considered significant in the hydrated sediments. Hence, a theory is to be established linking the seismic velocities with saturation of gas-hydrates and 'free-gas'. Since the model based on effective medium theory (EMT) has the potential to include all these effects, it is recommended to invoke the EMT for quantitative assessment of gas-hydrates and/or 'free-gas' from the estimated velocity information.

Till date, it is not fully understood how hydrates fill the pore spaces of sediments. Two end member distributions are (i) non-contact model in which hydrates are located in the pore voids without appreciable grain contacts and (ii) contact model in which hydrates are connected binding around the grains. From rock-physics based synthetic seismogram modeling for these two end member models, Ecker *et al.* (1998) and Carcione & Trinivella (2000) show that both P- and S- wave seismic velocity variation across the BSR are completely different. So both P- and S-wave seismic data are required to understand the distribution of hydrates, and hence four component (4-C) ocean bottom seismic (OBS) data become important for quantitative assessment of gas-hydrates and "free-gas". Modeling of wide-aperture seismic data using AVO tool will also help to differentiate the 'model of gas-hydrates with free-gas lying below' from the 'model of gas-hydrates without free-gas below'. 2-D waveform inversion of wide-angle OBS data at the most prospective sites will determine very accurate laterally/vertically varying velocity structure across the BSR. This will bring out the exact distribution of hydrates in a potential area. The velocity increase and/or drop against the background velocity trend can then be translated in terms of saturation of gas-hydrates and/or 'free-gas' across the BSR by invoking an effective medium theory leading to the quantitative assessment of resource potential.

Since the BSR is a good conversion point, converted waves recorded in OBS data can also be utilized to provide good constraint on the BSR depth. 2-D/3-D traveltime tomography of wide aperture (both P- and S- waves) seismic data that record both first arrivals and wide-angle reflections is a powerful tool to demarcate the prospective zones of gas-hydrates and/or 'free-gas' bearing formation within very limited time. Deep towed acoustic / geophysics system (DTAGS) can be utilized to provide high resolution (2m horizontal and 20m vertical) image and layer velocities

that result in greatly improved structural detail of BSR (Rowe & Gettrust *et al.*, 1993). The detailed velocity tomogram can reveal structures related to faults which, in turn, help to understand the migration path of fluid flow and formation mechanism. Geochemical methods supplement to understand the genesis of gas-hydrates. The molecular composition of hydrocarbon gases and isotropic composition of methane can distinguish between biogenic and thermogenic origin of gas-hydrates.

EXPLOITATION STRATEGY

For the extraction of methane from gas-hydrates, three principal methods can be considered: (i) thermal stimulation, (ii) depressurization and (iii) inhibitor injection (Sloan, 1990). To be realistic, economic exploitation of methane from gas-hydrates lying in deep-water regions is a distant prospect and cannot be expected in near future. But with the fast growth of technology, it is expected that the technique for commercial exploitation of gas (methane) from below the gas-hydrates will be developed soon. The Messoyakha field in the permafrost region of the western Siberia has produced more than 22 trillion cubic meter (approximately 1/3rd of world resources) of gas from gas-hydrates. Similar technology can be adapted to the marine environment by keeping view that the sites should be as close to the shoreline and accessible for production and transportation facilities. Abundant oil/gas resource potential deters advanced countries to promote exploitation technologies for commercial production of gas from gas-hydrates. Again different exploitation strategies are required for different environments. So it may become necessary for our country to develop the technology indigenously.

CONCLUSIONS

The consumption of fossil fuel is increasing at a rapid rate while discoveries are almost stagnant causing depletion of existing reserves. This has prompted many countries to explore this alternate source of energy. Gas-hydrates with abundant energy potential seem to be the best candidate as long as India is concerned, because of vast area of Indian deep-water regions lying between 500m to 3000m. Exploration and exploitation of this non-conventional source of energy may meet the ever-increasing requirement of energy for country like ours. On the other hand, it can reduce the environmental hazard, if exploited properly. Here lie the economic importance and societal benefit of studying the gas-hydrates in India.

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Gas Hydrates : Review

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INTRODUCTION

India's energy requirement has been growing at a steady rate of 6% per annum, which is considerably higher than the world's average of 1.5%. It is estimated that about 540 million tonnes of oil equivalent (mtoe) energy will be needed in the year 2010 as against the present requirement of 280mtoe. Coal oil and natural gas are the main resources of primary energy amongst the commercil fuels. Presently, 40% of the energy supply is being met using oil and gas, the share of natural gas being 8%.

A definite structural shift in favour of natural gas is envisaged in India's future plans and programmes for the oil and gas sector. Natural gas may emerge as the fuel of the choice and the ever widening gap between supply and demand needs to be bridged.

Indigenous sources are to be supplemented by import of gas and exploitation of unconventional sources, such as Coal-bed Methane, Gas Hydrates and *In-situ* Coal Gasification to bridge the gap.

Several national level initiatives to exploit these resources have already been taken. In addition, import of LPG and LNG has been de-licensed. Of the three unconventional sources metnioned above, gas hydrates (of Methane) seem to present the highest potential source as the quantity of methane gas contained in them is almost unlimited as compared to the conventional sources.

GAS HYDRATES

Gas hydrates are ice like crystalline compound consisting of natural gas (mainly methane) and water and occur at conditions of high pressure and low temperature. These consist of naturally occurring solids composed of water molecules forming a rigid lattice of cages, each containing a molecule of natural gas. The conditions necessary for the formation of hydrates are :

— Adequate gas molecules to stabilise of the hydrate cavities.

— Sufficient water molecules of form cavities.

— Temperature and pressure within the hydrate equilibrium region.

The main factors, which determine the formation Gas Hydrate Deposits (GHD) in porous media, are the presence of water and gas, appropriate temperature and pressure and the structure and composition of porous medium. The ultimate source of hydrate methane is the buried organic matter that can microbially or thermally produce methane. The amount and quality of organic matter present is critical to the methane generation process. Because gas-hydrate formation requires appreciable amounts of methane that greatly exceed the water solubility of methane, the amount of organic matter needed for gas hydrate formation is very large.

Deep-sea methane hydrates are found a few hundred meters beneath the continental slopes in the world ocean (more so in the subduction areas). The ice-like clathrate structure is stable up to a temperature of 10 to 30 °C beneath the sea-floor at the pressure generated by water depth of 800 meters.

The worldwide estimated hydrate based resource is given in Table I below:

Table I. Estimates of Oceanic Hydrates

Reference	(Cubic meters)
Makogon, Trofimuk & Others (1977)	5.25×10^{15}
Meyer (1981)	3.10×10^{15}
Dobrynin *et al.* (1981)	7.60×10^{18}
Makogon (1984)	1.50×10^{16}
Kvenvolden (1988)	2.00×10^{16}
Kvenvolden and Claypool (1988)	4.00×10^{16}
MacDonald (1990)	2.10×10^{16}
	(*Courtesy* : USGS)

Under the conditions prevailing in the India legal continental shelf, hydrates may occur at water depths exceeding 600 meters and extend up to a depth of more than 400 meters below the sea bottom, depending upon the hydrothermal and geothermal gradients.

CURRENT STATUS OF EXPLORATION OF GAS HYDRATES

USA

Most of the offshore sites have been discovered as a result of the Ocean Drilling Programme (ODP), which has been in existence for a number of years. The Ocean Drilling Programme is managed by Joint Oceanographic Institutions Inc., under contract with National Science Foundation (USA). The last excursion of the Deep Drilling Ship SEDCO-4, constituting Leg 164 of the Ocean Drilling Programme, undertaken during October-December 1995, was devoted exclusively towards gaining greater understanding of the Oceanic Gas Hydrates. This consisted of drilling a series of wells on the Blake Ridge in the south-eastern continental. This consisted of drilling a series of wells on the Blake Ridge in the south-eastern continental margin

of North America. The results indicated that gas hydrate occurs either in a finely disseminated form (and also as nodules) between 1.5 to 6% of the pore space in the sedimentary section between 200 to 450 meters below sea floor.

In an area of $26{,}000km^2$ region, around the Blake Ridge, where 'BSRs' are present, rough estimates indicate that about 10g.t. of methane carbon (650 Tcf) is stored in this region. Given the number of localities worldwide in which gas hydrate occurs, the results of ODP leg 164 provide further evidence that methane stored as gas hydrates in marine sediments represents a significant component of the global fossil fuel carbon reservoir.

In-place gas resources within the gas hydrates of the United States are estimated to range from 3,000 trillion cubic metres to 19,000 trillion cubic meters of gas at 95% and 5% probability levels, respectively. Although these ranges of values show a high degree of uncertainty, they do indicate the potential for enormous quantities of gas stored as gas hydrates. The in-place value for the entire United States is found to be 9,000 trillion cubic meters (mean probability). If this assessment is valid the amount of natural gas in gas hydrates is almost 300 times larger than the estimated total remaining recoverable conventional natural gas resources in the USA.

RUSSIA

Messoyakha gas hydrate field, located in the North-East of western Siberia of Russia has been producing gas from gas hydrates (Permafrost) for the last 25 years. Production of Methane hydrates occurred from the overlying reservoir seal. This production augmented the production of free gas. The process involves depressurization and injection of methyl alcohol. The gas production zone is at a depth of 870m and hydrate zone ranges from 250 to 870m. The maximum measured gas production in well #133 was $250{,}000m^3$/day and in well # 142 was $200{,}000m^3$/ day and after the alcohol treatment gas rates increased two to tenfold.

JAPAN

Japan, like India, finds itself amongst the countries which have to pay a very high price for the imported gas, has till to date the most ambitious "gas from gas hydrate" programme. Following the Petroleum Council Advice, MITI has planned a 5-year exploration programme beginning FY 1995, which includes drilling of 5 offshore stratigraphic wells and geophysical reconnaissance survey in 12 offshore areas. The budgeted cost of the Japanese 5-year Plan is around US $ 90 million. The Japanese Hydrate Programme is being carried out with the active participation of a large group of participants consisting of Oil Companies, Service and utility Companies, Research Institutes and Universities.

Japan National Oil Company (JNOC) is taking the lead by executing several projects for gas hydrate programme supported by MITI, Japan. During February

and March of 1998, Japanese drilled methane hydrate research well in the Mackenzie Delta in Canada under collaboration research work with the Geological Survey of Canada (GSC). In one of these projects, at a first milestone, JNOC has drilled in November 1999, A methane hydrate exploratory well in Nankai Trough area at a water depth of 950m, where typical BSRs have been observed on reflection seismic profiles. They have found hydrate in three layers with a total thickness of 16m. The sandy layers contained methane gas hydrate of about 20% of total sediment volume.

INDIA

After some initial publications on the subject by ONGC and NIO, in last decade, the interest in gas hydrate study was actively revived during the Indian Geophysical Union (IGU) conference held in December 1995 at NGRI, Hyderabad, which was attended by a large number of senior Geoscientists and Engineers from all over India.

Since then a small group of earth scientists and engineers belonging amongst others to GAIL, ONGC, NGRI, NIO and DGH have carried out preliminary work relating to gas hydrate occurrence in Indian legal continental shelf, based on existing geological, geochemical and seismic data.

A National Gas Hydrate Programme (NGHP) was formulated in early 1997, which is monitored by a Steering Committee headed by the Secretary, MOP&NG with ONGC, GAIL, OIL, DGH, NIO & NGRI as the members. GAIL was entrusted the job of Co-ordination for pursuing various activities under this programme.

Subsequently, the compilation of various geophysical and oceanographic data has indicated the occurrences of gas hydrate deposits in offshore India. GAIL, in association with NIO, has prepared for the first time the Gas Hydrate Stability Zone Thickness Map of India, based on theoretical conditions of occurrence of gas hydrates in Indian offshore.

In continuation of the project, NGRI, at the behest of GAIL prepared a comprehensive report for the purpose of identification of most suitable areas for hydrates prospecting, based on existing geological, geochemical and seismic data. A large number of 'BSRs' and 'BSR' like features have been identified both off west and east of India in water depths corresponding to 'Hydrate Stability Zone'.

Seismic data pertaining to various international agencies like the Lamont Doherty Earth Observatory, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, the National Oceanic and Atmospheric Administration (NOAA) of USA has been procured through National Geophysical Data Centre (NGDC), USA through NGRI, Hyderabad. The interpretation of these data has brought our several prospective BSRs in Western Offshore, Eastern Offshore and in Andaman area. One of the BSRs in western offshore (offshore Goa) has an extension

of 126km and is underlain by "wipe out" zone which is an indication of massive free gas.

Seismic data of 50001km of NAtional Institute of Oceanography (NIO), Goa has been processed and interpreted for the occurrence of gas hydrate. That study has revealed several BSRs in western Offshore of India.

The compilation of all these results led to the project "Exploration of Gas Hydrate in Offshore Goa" which covers an area of 64000 sq. km and is approximately 200km away from the coast. The water depth in this area ranges from 900-2500 meters. The projectisation work needs to be carried out and includes acquisition of fresh seismic data followed by drilling of 2-3 exploratory wells for the Establishment of gas resource associated with hydrate.

Subsequently, multi-channel data of ONGC in Kerala-Kondan deepwater area were visually examined for the presence of gas hydrates. Several BSRs have been recognised in this area. A typical fairway for gas hydrate occurrence has emerged in the offshore Goa. Aproximately, 43001km of this data has been selected for special processing to identify seismic attributes of gas hydrates for further exploration. This will facilitate the identification of areas/gaps where additional fresh data are required with newer acquisition parameters tuned to gas hydrate exploration.

Besides the works of NIO and NGRI, Directorate General of Hydrocarbons (DGH) has recently acquired multi-channel data in East Coast and in Andaman offshore. This data have clearly manifested the occurrence of BSRs for gas hydrates and associated free gas below it. Two prospective areas have been identified in Andaman offshore at water depth of 850 and 1400 meters. ONGC has also reassessed the existing deep-water multi-channel data and demarcated the offshore areas in terms of highly prospective, moderately prospective and low prospective for exploration of gas hydrates. ONGC has identified strong BSRs in Krishna Godavari offshore at approx. 1300 meters of water depth and planned acquisition of additional seismic data to precisely map the gas hydrate in this area.

DEEP WATER TECHNOLOGY

There have been a dramatic improvement in the deep water oil and gas exploration capabilities in the last 2-3 years. At the same time there is also a distinct reduction in deep water development costs and offshore projects are becoming commercially viable.

Recently 'AKER' of Norway has signed an MOU with 'EIL' for collaboration in deep water technology. AKER been associated with the design, construction and installation of most of the deep water projects (Auger, Mars, Ram Powell etc.)

The oceanic deposits of gas hydrates are known to be occurring at water depth below 700m. The feasibility of pipeline transportation of gas from gas hydrate should therefore be established for water depth from depth from, say, 700-3000m. In this context, EIL in association with GAIL has undertaken a feasibility study for deepwater pipeline technology.

Drilling in waterdepth of 1000m plus is progressively taking place in Deep water exploration blocks of North Sea, Gulf of Mexico, and offshore Brazil. Deep water Exploration & Production (E&P) Records are gradually becoming higher & higher. Petrobras deep water specialists developed and applied an engineering solution that made it possible to bring on stream the first oil from the giant Roncador Field in Camops Basin, Brazil. It flows from the world's deepest producing well at a water depth of 1853m, and is a fast track project: only two years after discovery. The previous record for the same category was also held by Petrobars: 1709 meters in the nearby Marlim Sul Field, offshore Brazil.

This, at present, Deep sea drilling and production technology is available for operation up to 2000m. Shell has undertaken a detailed study commingling the individual components of deepwater technology towards exploitation of gas hydrates. Shell's consensus is that **there do not appear to be any major technical "Show Stopper" to hydrate associated gas production if suitable accumulations can be found. However, the economics of drilling, completing and producing deepwater "gap only" wells could well be the only major hurdle yet to be resolved.**

FUTURE EXPLORATION TECHNOLOGY TRENDS

Once a BSR is identified, the amount of hydrate, its mobility and recoverability (*i.e.*, permeability and formation strength) has to be estimated. The key to extracting this information from seismic data is rock physics. Amplitude Varion with Offset (AVO) is a petro-physical imaging tool and this analysis reduces risk. The reflection coefficient variation with offset is dependent on changes in medium *p* wave velocity (Vp), s wave velocity (Vs) and the density (p), thereby providing the theoretical basis for AVO analysis.

Multicomponent seismic data (4-C) are being collected on the shelf area of various offshore basins. Efforts are on to collect similar data in the deep water basins by deploying the 4-C ocean bottom cable (OBC) in the dragged mode.

Seismic waveform contains much information that is ignored under standard processing scheme; seismic waveform inversion seeks to use the full information content of the recorded wave field. The method proceeds from a starting model to refine the model in order to reduce the waveform misfit between observed and the modeled data. The model data are computed using a full wave equation.

The Deep Towed Acoustic Geophysical System (DTAGS) is particularly well suited to provide high resolution mapping of sub bottom structures in deep water and to map the shape and structure of the BSR for methane gas exploration. Source and receiver array are towed between 200-300m above the sea floor tohave data to resolve sediment structural details < 5 mts in thickness within the upper 600-700m of sediments.

CONCLUSION

Geological and geophysical studies carried out by various participating organizations under National Gas Hydrate Programme has led to identification of prospective areas in eastern and western offshores of India. Although the prospective areas lie in deepwater, with rapid progress in deep-sea technologies and reduction in associated costs, these prospects seem to be viable for exploitation to produce gas in commercial quantities in the near future. In India, existing technologies need to be upgraded and new technologies used to be acquired to embark upon commercial exploitation of gas hydrates.

It is a matter of great satisfaction that we, in India started national programme on gas hydrate in 1997 at the same time when other countries like Japan and Russia started similar programmes. A firm commitment and concerted efforts in this area of great potential and continuous investments to R&D and commercial exploitation of gas hydrates programme would result in major breakthrough to our energy resources very soon. This will have a great impact on energy scenario of India, thereby enter into a new era of energy resources.

Global Warming—Kyoto Protocol

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The subject of global warming has become an important issue for scientists, policy makers and public alike during the last one decade. What are the perturbations caused to the natural environment, how these affect the future climate and how one can control these changes are some of the major questions to be answered. Atmospheric abundances of key greenhouse gases have increased beyond the natural variabilities due to anthropogenic perturbations. The global average temperature of the Earth's surface is observed to be rising and is further expected to rise by the end of this century between 0.9 to 3.5 °C from the present. This will cause many related climatic changes. Various international organizations like the United Nations are trying to convince the developed and the developing countries to limit the emissions of the greenhouse gases without slowing down the developmental activities.

INTRODUCTION

The Earth is the only planet of the solar system and in the entire universe, known so for, where life exists. This special feature of the Earth is due to its unique atmosphere and location from the Sun. The Earth is the only place where water exists in all its three forms, viz. solid, liquid and gas. The Earth's atmosphere contains major gases like nitrogen (78%), oxygen (21%) and argon (0.93%). But there are various other gases (see Table I) which also pay many important roles. This atmosphere not only gives us enough oxygen to breath, but it also protects us from the deadly ultraviolet radiation coming from the Sun. However, due to agricultural and industrial revolutions, this unique atmosphere is getting polluted. Stratospheric ozone depletion, particularly in the Antarctic and Arctic regions, is one such example refrigerators and airconditioning, have been found responsible. This paper describes the impact of increasing pollution on the future climate through the greenhouse effect and how the Kyoto Protocol is planned to control these emissions.

Table I: *Composition of Atmospheric Air*

(a) Major Constituents		
Nitrogen (N_2)	—	78.08%
Oxygen (O_2)	—	20.95%
Argon (Ar)	—	0.93%
(b) Minor Constituents		
Water Vapour (H_2O)	—	upto 10,000 ppmv**
Carbon Dioxide (CO_2)	—	360 ppmv
Ozone (O_3)	—	upto 10 ppmv
Methane (CH_4)	—	1.7 ppmv
(c) Trace Constituents		
Nitrous Oxide (N_2O)	—	315 ppbv
Carbon Monoxide (CO)	—	- 100 ppbv
CFCs	—	- few hundred pptv
Halons	—	- few pptv

**ppmv — Parts per million by volume
ppbv — Parts per million by volume
pptv — Parts per million by volume

GREENHOUSE EFFECT

The Sun's visible and part of the ultraviolet radiation reach the Earth's surface without much absorption. To be in the thermal equilibrium, the Earth radiates back the energy in the form of infrared (IR) radiation which peaks around 10μm wavelength region. However, this IR radiation is trapped by a number of gases known as greenhouse gases. This effect of allowing the solar radiation to reach the Earth's surface and absorbing the Earth's outgoing IR radiation is known as 'the greenhouse effect' because of its analogy to common greenhouses, which are used to grow vegetables and flowers and heat homes in cold countries. The solar cooker also works on the same principle. This keeps the surface of the Earth warm and inhabitable. The absorption of the IR radiation is done mostly by H_2O and CO_2, but N_2O, CH_4, O_3 and some of the CFCs also make significant contributions.

Without these greenhouse gases the Earth would have been cooler by about 35 °C. This can easily be calculated by equating the solar energy received at the Earth's surface to that emitted by it.

$$\text{Total energy received} = \pi R^2 (1 - \alpha)$$

$$\text{Total energy radiated} = 4\pi R^2 \sigma T_e^4$$

$$T_e = [S (1 - \alpha)/4\sigma]^{1/4},$$

where S = Solar flux = 1.367×10^6 erg cm^{-2} s^{-1}

and α = Average albedo of the Earth's surface = 0.3

and σ = Stefan-Boltzmann Constant = 5.67×10^{-5} erg cm^{-2} deg^{-4} s^{-1}.

By substituting these values in eqs. 1, the equilibrium temperature of the Earth is calculated to 253 °K. Thus the temperature of the Earth would have been –20°C had there been no atmosphere. In that case, it would have been a frozen lifeless planet. We know that the present global average temperature is + 15 °C, which is warm enough for the survival of life. Similar greenhouse effects occur on other planets also (see Table II). Venus has a very thick atmosphere about 90 times that of the Earth that too mostly (> 90%) of CO_2. The greenhouse effect is maximum there.

Table II: *Concentrations, Lifetimes and Global Warming Potentials (GWP) for Major Greenhouse Gases*

Gas	Pre-Industrial Concentration (1860)	Present Tropospheric Concentratin	GWP (100 yr. Time Horizon)	Atmos-Pheric Lifetime (years)
Carbon dioxide (CO_2) (ppmv)	288	366	1	120
Methane (CH_4) (ppbv)/	848	1745	21	12
Nitrous oxide (N_2O) (ppbv)	285	312	310	120
CFC-11 (CCl_3F) (pptv)	Zero	262	3,800	50
CFC-12 (CF_2Cl_2) (pptv)	Zero	533	8,100	102
HCFC-22 ($CHClF_2$) (pptv)	Zero	118	1,500	12
Sulphur hexafluoride (SF_6) (pptv)	Zero	3.5	23,900	3,200
perfluoroethane (C_2F_6) pptv)	Zero	4	9,200	10,000
Tropospheric Ozone (ppbv)	~50	~50	1200-200	Months/Years

ROLE OF GREENHOUSE GASES IN GLOBAL WARMING

The Greenhouse gases absorb the Earth's radition in specific bands determined by their chemical structures. The effectiveness of the absorption depends upon the strength of the bands and on the concentrations of the gases. Absorption by water vapour and CO_2 is very strong[1]. If other gases also absorb in the bands of H_2O and CO_2, the contribution of the gases will be insignificant. However, there is a region of 8μm to 12μm known as 'atmospheric window' where absorption by the main greenhouse gases is very weak (see Fig. 1). Other trace gases like ozone, which has a peak absorption at 9.6μm, methane, nitrous oxide and specially CFCs have absorption in this or near this 'window' region. Even though their concentrations are small, they still contribute significantly. Since the concentrations of CFCs are in pptv levels, absorption by them even at the centre of the band is not saturated. This makes their greenhouse effect increase linearly with increasing concentrations unlike for CO_2 and some other gases.

CHANGES IN THE CONCENTRATIONS OF GREENHOUSE GASES

Water vapour is the single most important greenhouse gas. However, it is controlled mainly by natural processes. There is no evidence, at present, suggesting any change

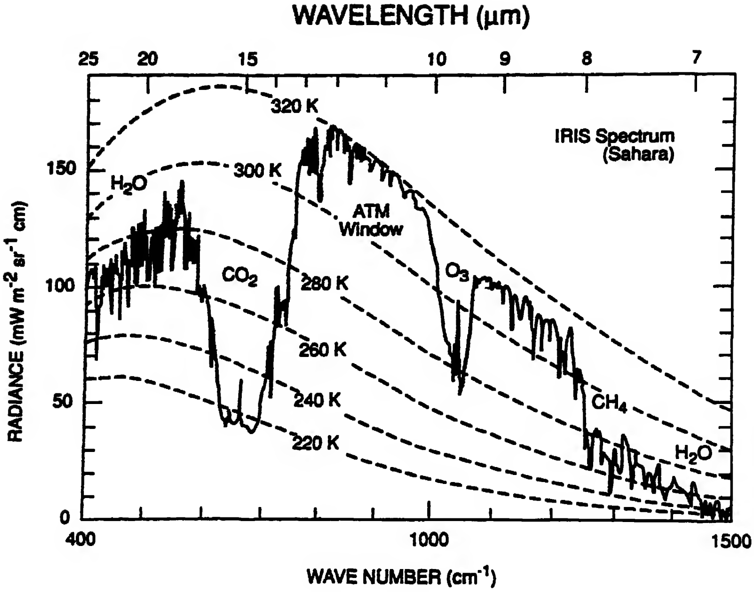

Fig. 1. Specturm of the Earth's obtained by a spectrometers on board the Nimbus-3 satellite on a clear day (Hanel *et al.*[2]).

in its concentrations. We will discuss below other greenhouse gases, which are increasing due to anthropogenic activities.

CARBON DIOXIDE (CO_2)

Global average concentration of CO_2 has increased from its pre-industrial value of 280 ppmv to its present value of about 366 ppmv (Fig. 2). The increase CO_2 concentration since 1958, when the first regular measurements were made, accounts for only 58% of the total amount released by fossil fuels burning. Oceans are the primary sink for the excess atmospheric CO_2. Atmospheric lifetime of CO_2 is about 120 years (Table III), but it is mainly due to the exchange between various reversoirs since there is no photochemical loss in the lower atmosphere.

The total atmospheric reservoir of CO_2 at present is equivalent to 750 Gtc*, which is much smaller than the terrestrial biosphere amounting to 2050 GtC. However, the oceanic reservoir at 39,000 GtC is the biggest of all[4]. There is a large exchange of fluxes between the atmosphere, land and ocean. Emissions from fossil fuel combustion and cement production are estimated to be 5.5 GtC/yr and emissionfrom deforestation is 1.6 GtC/yr. The total emission accounts for 7.1 GtC/yr. Out of this 3.3 GTC/yr is stored in the atmosphere and 2.0 GTC/yr taken up by the oceans. Uptake by the regrowth of forest in the modern region is about 0.5 GtC/yr. It is not clear where the rest (1.3 GtC/yr) of the emission goes[4,5].

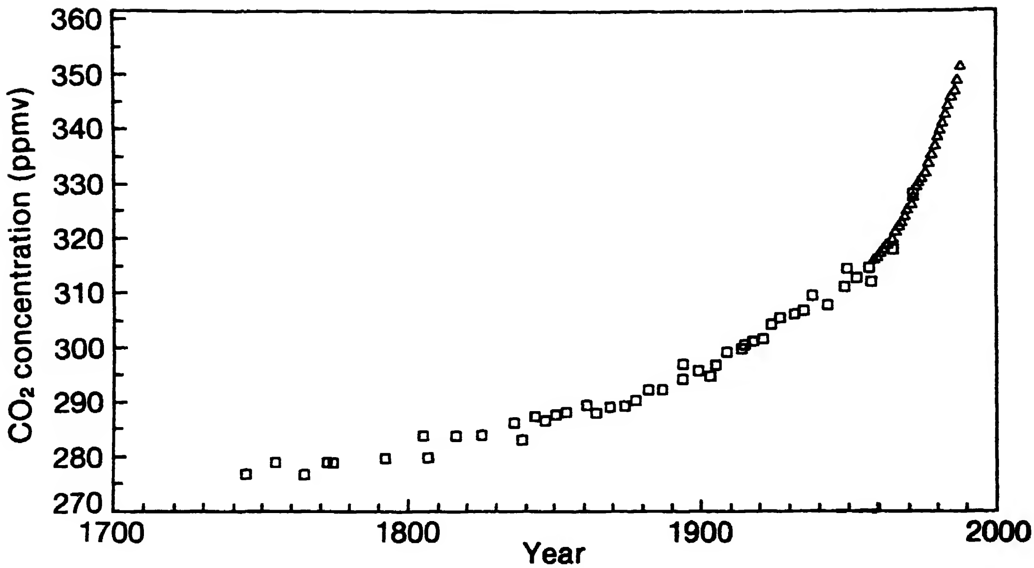

Fig. 2. Atmospheric CO_2 increase during the last 250 years (IPCC[3]).

The current greenhouse heating due to carbon dioxide is about 50 Wm^{-2}. This has increased by about 1.3 Wm^{-2} since the pre-industrial times[4,5]. Warming of the oceans due to greenhouse effect is likely to reduce the the uptake of CO_2 causing positive feedback in the global warming.

METHANE (CH_4)

Methane is another naturally occurring greenhouse gas whose concentration is increasing in the atmosphere due to anthropogenic activities like agriculture, waste disposal, fossilfuel production and its use. About 32% of atmospheric methane originates from fossil fuel burning. Major sink of methane is the photochemical oxidation by OH in the troposphere (lower part of the atmosphere upto about 15 km.) Methane concentration has increased from a value of about 700 ppbv in the pre-industrial time to about 1745 ppbv currently (Fig. 3). Over the last 30 years, its growth rate has been changing. In the later 1970s, its concentration was increasing by about 20 ppbv/yr, while during 1980s the growth rate dropped to 9-13 ppbv/yr and become almost zero in 1992. But methane is growing again (~5ppbv/yr)[5,6]. This behaviour has puzzled the scientists. Table III also shows the Global Warming Potential (GWP) of various gases. It provides a simple representation of the relative time integrated radiative forcing resulting from the instantaneous release of a unit mass of a gas compared to CO_2. The GWP of methane is 21, which indicates that it is 21 times more effective than CO_2.

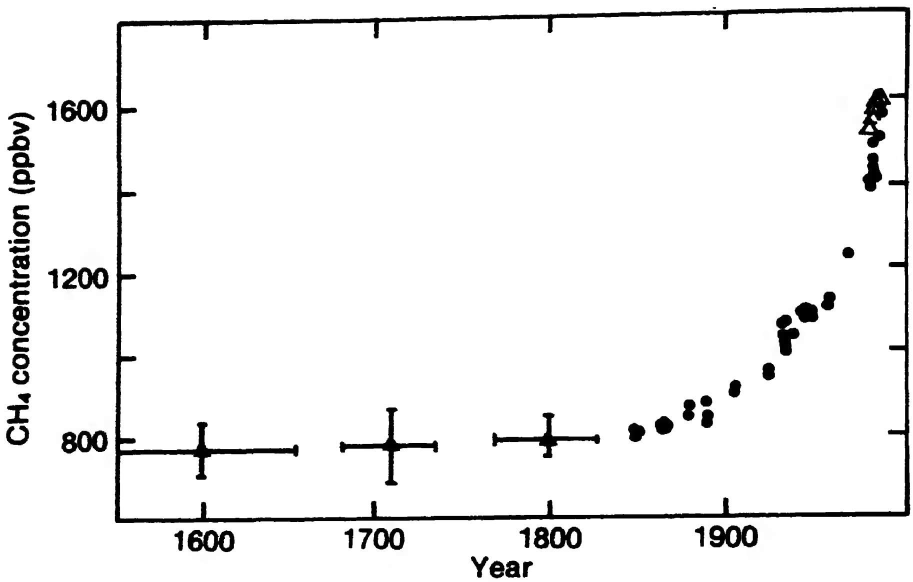

Fig. 3. Variation of atmospheric CH_4 for the past four centuries (IPCC[3]).

The radiative forcing due to change in methane concentrations from its preindustrial value is almost 0.47 Wm^{-2} [4 & 5] Since micobial activities increase with temperature, the global warming may result in higher emission of methane from wetlands. This again will cause positive feedback.

NITROUS OXIDE (N_2O)

Sources of atmospheric nitrous oxide include microbial processes in soil and water, nitrogen fertilizers and fossil fuel and agriculture burning. Anthropogenic sources are about half of the natural sources. It is removed mainly by photolysis in the stratosphere (region of the atmosphere above the troposphere between 15 and 50km). Concentration of N_2O has increased from a pre-industrial value of 275 ppbv to about 312 ppbv (Fig. 4). Atmospheric lifetime of N_2O is about 120 years. Its current growth rate is about 0.2%/yr. Its GWP is 310 times that of CO_2 (Table III).

Table III: *Greenhouse Effect on Other Planets*

Planet	Surface Pressure (w.r.t. Earth)	Main Greenhouse Gases	Surface Temperature Greenhouse Effect	Observed Surface Temperature
Earth	1	~ 0.04% CO_2 ~ 1% H_2O	-20 °C	+15 °C
Venus	90	> 90% CO_2	-46 °C	477 °C
Mars	0.007	> 80% CO_2	-57 °C	-47 °C

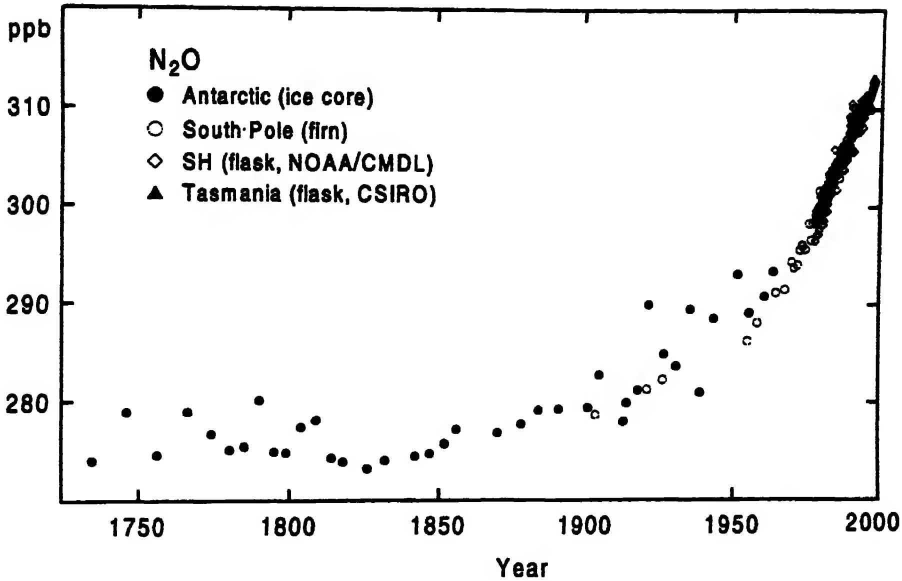

Fig. 4. Long-term variations of atmospheric N_2O based on various data sets (WMO[6]).

The radiative forcing due to the change in concentrations of N_2O from its preindustrial abundance is about 0.14 Wm^{-1} [4 & 5].

HALOCARBONS (HCS)

These are the hydrocarbons containing fluorine, chlorine, bromine or iodine. Chlorofluorocarbons (CFCs) are sub-groups of this class, which contain chlorine and fluorine. Many of these are effective greenhouse gases as they absorb the thermal radiation in the 8-12μm 'window' region. CFC-11 and CFC-12 are the two main anthropogenic species, which are found to deplete atmospheric zone. Measurements of the vertical distribution of various HCs made from Hyderabad using balloonborne cryogenic air sampler show that chlorine and bromine from most of these gases are released in the lower stratosphere due to their photodissociation[7]. They were known as released in the lower stratosphere due to their photodissociation[7]. They were known as the 'wonder' chemicals when they were found in the 1930s. They are now being phased out and being replaced with new species, which are 'ozone friendly'. Current concentrations of CFC-11 and CFC-12 are 262 pptv and 533 pptv respectively. Eventhough these gases are being phased out, they will stay in the atmosphere for a long time due to their long lifetimes (see Table III). Several other important HCs and other gases are also included in Table III. The lifetimes and GWP's of perfluoroethane and SF_6 are very large. However, their concentrations are very small[5 & 7].

The total radiative forcing due to these CFCs and other halocarbons is estimated to be 0.25 Wm^{-2} due to changes in their concentrations from pre-industrial times[4 & 5].

ATMOSPHERIC OZONE (O_3)

Atmospheric ozone plays an important role in the heat budget of the atmosphere. The change in the temperature gradient from decreasing in the troposphere to increasing in the stratosphere is solely due to absorption of solar UV radiation by stratospheric ozone. The total amount of ozone in the stratosphere is about 90%, while the remaining 10% is in the troposphere. Measurements made from Thumba near Trivendrum using rocket borne sensors show that ozone peaks around 27km height in the tropical region[8]. As mentioned earlier, there is a decrease in the stratospheric ozone due to CFCs. However, there are evidences of ozone increase in the troposphere, particularly in and near big industrial regions and cities where photooxidation of CO and hydrocarbons can cause ozone production[6&9]. Since tropospheric ozone absorbs the Earth's thermal radiation, it also causes global warming. However, since there are large spatial and temporal variations in tropospheric ozone, its long-term trends are difficult to estimate.

The loss of ozone in the lower stratosphere over the past 15-20 years has led to a globally average radiative forcing of -0.1 Wm^{-2}. The best estimator radiative forcing due to change in tropospheric ozone is about 0.4 Wm^{-2}[5].

AEROSOLS

Aerosols are the suspended particles in the air of diameter in the rang of 0.1μm to 10μm. These could be dust particles or water droplets originated from natural (dust storm, breaking of oceanic waves) or manmade (fossil fuel and biomass burning) processes. Aerosols affect the radiation balance in the atmosphere by (i) scattering and absorption of radiation, (ii) affecting the could, and (iii) heterophase chemistry, such as ozone depletion through polar stratospheric clouds.

In general, aerosols have cooling effect, but soot type of aerosols could induce warming. The radiative forcing due to aerosols depends upon their size, shape chemical composition and the height of the layer. Also, there is large spatial and temporal variability. The radiative forcing calculation for aerosol is highly uncertain due to all these factors. Recent direct measurements of radiative forcing due to aerosols in the Indian Ocean give higher values than the average model compared value[10].

Fig. 5 gives summary of the global mean radiative forcing for different species. Major contribution in the radiative forcing is by CO_2, CH_4, N_2O and the halocarbons. The total radiative forcing by these gases is estimated to be 2.45 Wm^{-2} with main contribution from CO_2[5]. The radiative forcing by change in trospospheric ozone from the pre-industrial time is estimated to be in the range of 0.6-2.0 Wm^{-2}. Depletion in stratospheric ozone causes negative radiative forcing. It is estimated to be about

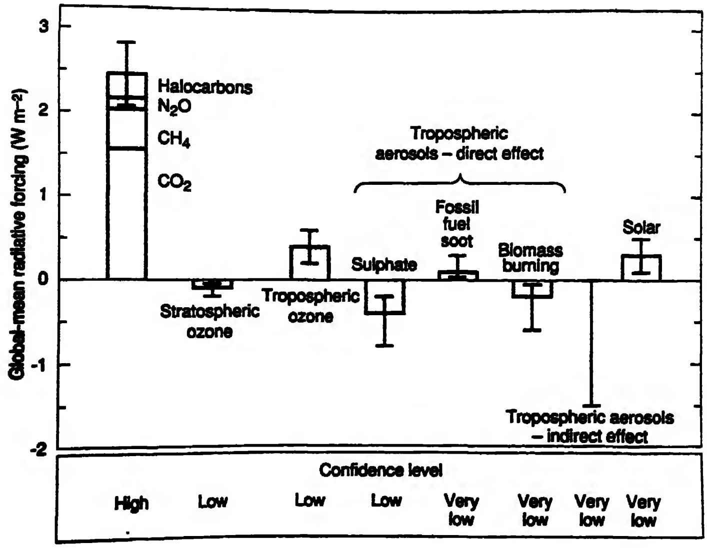

Fig. 5. Estimates of the globally and annually averaged radiative forcing due to change in concentrations of greenhouse gases and aerosols from the preindustrial times (IPCC[5]).

-0.1 Wm^{-2}. Sulphate aerosols from fossil fuel burning contribute a radiative forcing of -0.66 Wm^{-2}. On the contrary, soot aerosols absorb solar radiation in the visible wavelength region giving rise to a positive forcing[5]. The best estimate for the radiative forcing by the soot particles in about +0.1 Wm^{-2}. The other type of aerosols are from biomass burning. The radiative forcing from this type of aerosols is calculated to be -0.2 Wm^{-2}. These estimates for ozone and aerosols are very poor and have large uncertainties.

TEMPERATURE CHANGE

Recent analysis of the past global average temperature show signature of the global warming due to the net radiative forcing caused by changes in the concentrations of greenhouse gases from the pre-industrial times to the present. Fig. 6 shows the global average (land surface air and sea surface) temperature difference from 1861 to 1994 relative to1961 to 1990 period[5]. The mean surface temperature has increased by about 0.3 to 0.6 since the late 19th Century and by 0.2 °C to 0.3 °C over the last 40 years. This increase in temperature is against the glacial-interglacial changes with cycles that last about 1,00,000 years based on ice core data[11]. According to this paleoclimate record, the Earth's temperature should be on a declining trend. The decade 1990s was warmer and the year 1998 was observed to be the warmest year so far[12]. The Indian Data also show an increase trend (Fig. 7). The average increase rate is estimated to be about 0.4 °C/century[13].

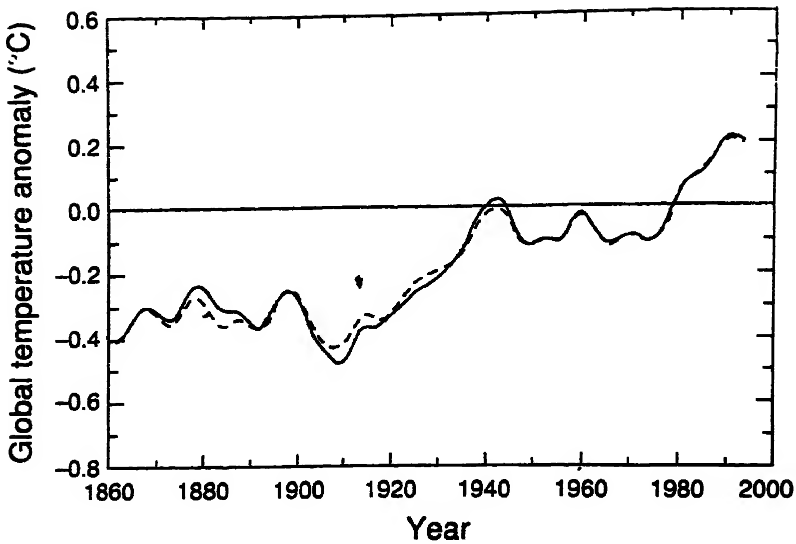

Fig. 6. Change in combined land-surface air and sea-surface temperature during 1961-1994 relative to 1961-1990 period (IPCC[5]).

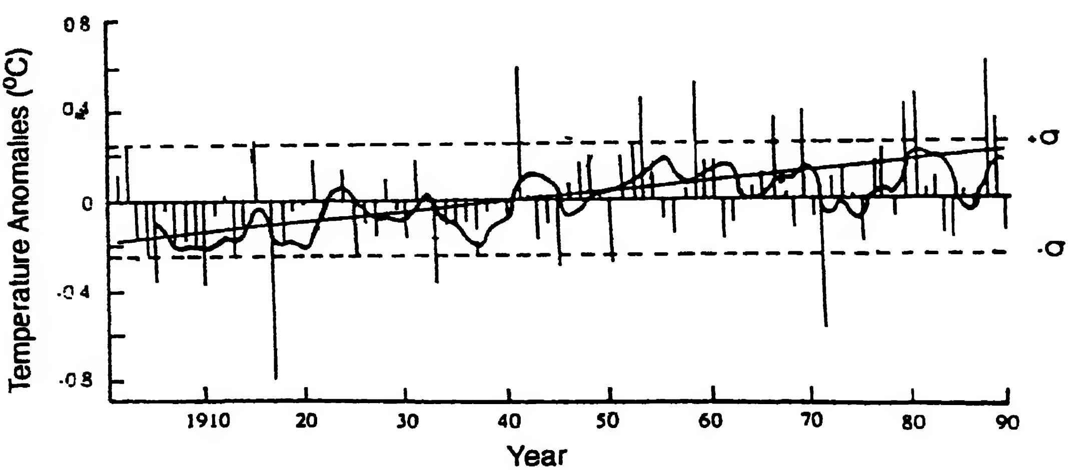

Fig. 7. Observed change in average annual temperature over India for the period 901-1990. The thick curve is the 5 years running mean (Plant *et al.*[13]).

FUTURE CLIMATE CHANGE

How the climate will change in future due to increasing concentrations of various potential greenhouse gases ? This has been a major concern to the scientists, policy

makers and public. The Intergovernmental Panel on Climate Change (IPCC) has been reviewing this subject since 1990 when they brought out their first assessment[3]. This has been reviewed from time to time. Since the future trends are uncertain, the model calculations are made using various future scenarios. All the six emission scenarios used in this IPCC 1990 report imply increases in greenhouse gas concentrations from 1990 to 2100. Over this period, the projected increases are by 35% to 170% for CO_2. 22% to 175% for CH_4 and 26% to 40% for N_2O. Fig. 8 shows increase in CO_2 concentrations based on various scenarios. These increases in the concentrations of greenhouse gases will change the radiative forcing and will result in temperature change. Fig. 9 shows the projected global mean temperature change for 21st century[5]. The models project and increase in the global mean temperature between 0.9 °C and 3.5 °C by the end of this century. In all cases, the average rate of warming would probably be greater than what is seen in the last 10,000 years. Due to the thermal inertia of the oceans, global mean temperature would continue to increase beyond 2100 even if concentrations of greenhouse gases were stabilized at that time. While CO_2 is the most important anthropogenic greenhouse gas, the other greenhouse gases also contribute significantly (about 30%) to the projected warming.

Due to increase in global temperature, the ice in the polar regions and other places will also melt. This is likely to rise the global sea level. Based on the models, the global average sea level rise is expected to be in the 35-55cm range (Fig. 10) for

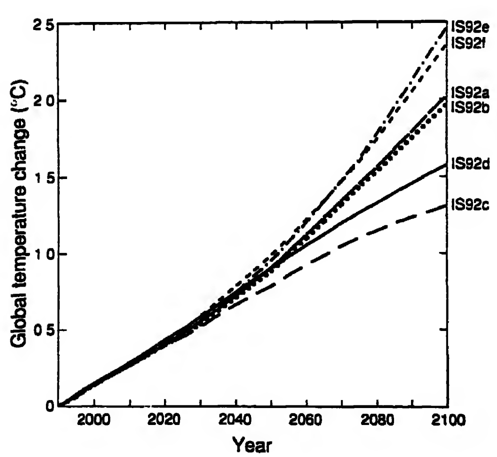

Fig. 8. Expected increased in atmospheric CO_2 concentrations for the six emission scenarios as described mean surface temperature changes from 1990 to 2100 for the six emission scenarios (IPCC[5]).

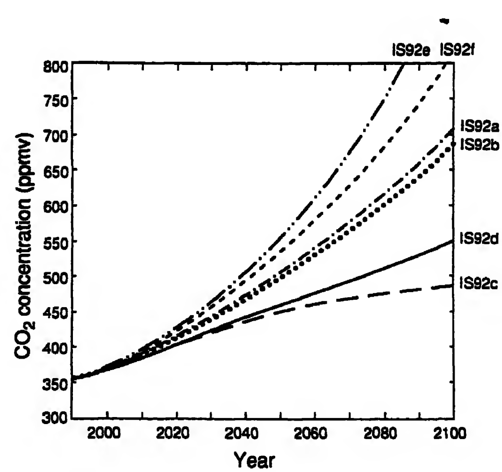

Fig. 9. Computed global mean surface temperature changes from 1990 to 2100 for the six emission scenarios (IPCC[5]).

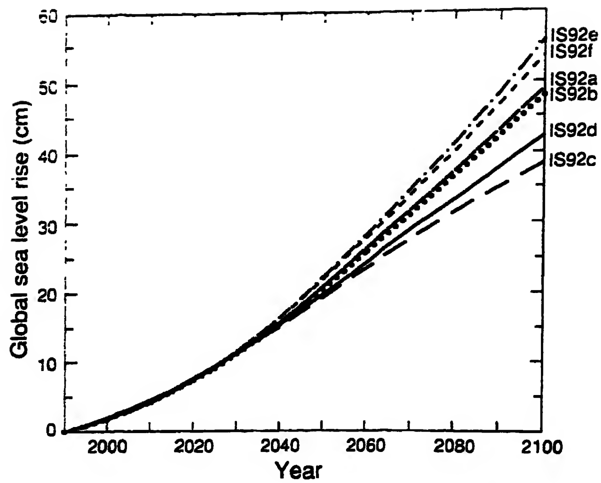

Fig. 10. Computer global mean sea level rise from 1990 to 2100 for the six emission scenarios (IPCC[5]).

all the six scenarios[5]. Global temperature as well as sea level rise will not occur uniformly around the globe. Models suggest that the regional responses could differ substantially. A model study, which includes greenhouse gases and aerosol forcing, for the Indian region shows a decrease of about 0.5mm/day in summer monsoon rainfallfor the decade 2040[14].

FRAMEWORK CONVENTION ON CLIMATE CHANGE (FCCC)

Climate change was recognized as a major global concern at a World Climate Conference as early as in 1979. Unusuallyhigh temperatures in 1980s were suspected to be due to accumulation of greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 to assess the seriousness of the climate change problem and make recommendations. The first report of the IPCC in 1990 stated that emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases. This will result in additional warming of the Earth's surface.

In early 1991, negotiations began on a global treaty on climate change, which came to be known as the United Nations Framework Convention on Climate Change (UNiFCCC). This was adopoted at the United nations Conference of Environment and Development (UNCED) at Rio de Janeiro in June 1992. The UNFCCC has beenratified by 166 countries. India signed this treaty on June 10, 1992 and was the 38th country to ratify it on November 1, 1993. The convention entered into force on March 21, 1994. The objectives of the treaty are to achieve stabilization of greehouse gases in the atmosphere at a level that would prevent dangerous anthropogenic

interference with the climate system, to ensure that food production if not threatened and to enable economic development to proceed in a sustainable manner. The convention provides commitments to various parties to reduce their emissions based on the principles of 'equity' and 'common but differential responsibilities". According to FCCC, the developed countries were asked to stabilize their greenhouse gas emissions at 1990 level by 2000.

KYOTO PROTOCOL

The overwhelming resopnse to the FCCC, which was ratified by 166 countries (developed and also developing), endorsed the climate change problem as well the need to find a solution. However, the targets were inadquate for achieving the long-term need and did not specify abatement and also targets beyond 2000. It was also realized that the developed nations would not be able to reach emission levels below 1990 levels by the year 2000. In view of these limitations, efforts were initiated. The parties of the FCCC met at Kyoto, Japan in December, 1997 to discuss the details of an international treaty designed to establish legally binding limitations on emission of greenhouse gases[15-18]. The main features of the negotiations arrived at the Kyoto Protocol are the following :

1. It covers six major greenhouse gases, which include CO_2, CH_4, N_2O, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6). For the first time, gases other than CO_2 are also covered.
2. Annexure I parties (developed countries) would reduce their overall emissions by 5.2% below 1990 levels by the 2008-12 period. The details of the emission reduction are given in Table IV. Nations with the highest CO_2 emissions—the United States, Japan and most European countries are expected to reduce their emissions by a range of 6-8%. Russia, New Zealand and Ukraine will be allowed to stabilize at 1990 levels. Australia will be allowed to raise its emission by 8% above 1990 levels.
3. Annexure I parties can use net changes in greenhouse gas emissions resulting from human induced land use forestry activities, limited to afforestation, reforestation and deforestation since 1990, to meet their commitments.
4. Introduction of the following three flexibility mechanisms which are recognized as the strength of the Protocol. These are also the most controversial issues.

(i) Joint Implementation (JI)—This allows developed countries to get credits towards their targets through project based emission reductions in other such countries.

(ii) Clean Development Mechanism (CDM)—CDM allows developed countries to invest in projects in developing countries that reduce greenhouse gas emissions and receive credit for the reductions. India and US have signed such an agreement in March, 2000.

Table IV: *Commitments to Limit or Reduce Emission of Equivalent CO_2 from 1990 to 2010 by ANNEX. 1 Parties as agreed to at Kyoto in 1997.*

Party	Allowed 1990-2010	Observed 1990-1995
European Union*	–8%	–1%
Austria	–8	–3
Belgium/Luxembourg	–8	–3
Denmark	–8	+1
Finland	–8	+18
France	–8	–4
Germany	–8	–9
Greece	–8	+7
Ireland	–8	–1
Italy	–8	–1
The Netherlands	–8	+7
Portugal	–8	+49
Spin	–8	+14
Sweden	–8	+7
U.K. and N. Ireland	–8	+4
OECD, except EU :	(–6)	+8
Australia	+8	+8
Canada	–6	+9
Iceland	+10	–4
Japan	–6	+8
New Zealand	0	+16
Norway	+1	+9
Switzerland	–8	–5
United States	–7	+7
Countries in economic transition**:	(–1)	–29
Bulgaria	–6	n.a.
Croatia	–5	n.a.
Czech Republic	–8	–23
Estonia	–8	n.a.
Hungary	–6	–15
Latvia	–8	n.a.
Poland	–6	n.a.
Romania	–8	n.a.
Russian Federation	0	n.a.
Slovakia	–8	n.a.
Slovenia	–8	n.a.
Ukraine	0	n.a.
Non–Annex–I Parties	–	+25

*Members of the European Union will implement their respective commitments in accordance with the provisions of Article 4 of the Convention.

*Countries that are undergoing the process of transition to a market economy. (Developing Countries)

OECD : Organization for Economic Cooperation and Development.
EU : European Union
n.a. : Not available

(iii) Emission Trading (ET)—Under this scheme, a nation whose emissions fall Below its treaty limit can sell the credits for its remaining emissions to another nation.

The Kyoto Protocol is considered only a first step forward for achieving the goal. It wll enter into force only when 55 nations ratify the treaty including enough developed countries to account for 55% of the global CO_2 emissions in 1990. By 2005, all industrialized nations those ratify the accord must show demonstrable progress towards fulfilling their respective commitments under the Protocol. The share of the United States in the Global emission of CO_2 in 1990 was ~ 23%, that of European Union (EU) ~ 15% and that of Japan ~ 5%. (See Fig. 11). This means that protocol will not come into force until it has been ratified by a number of these countries. The Protocol has been signed by 84 countries, but only 22 countries have ratified it as on Jan., 13, 2000 (See Table V).

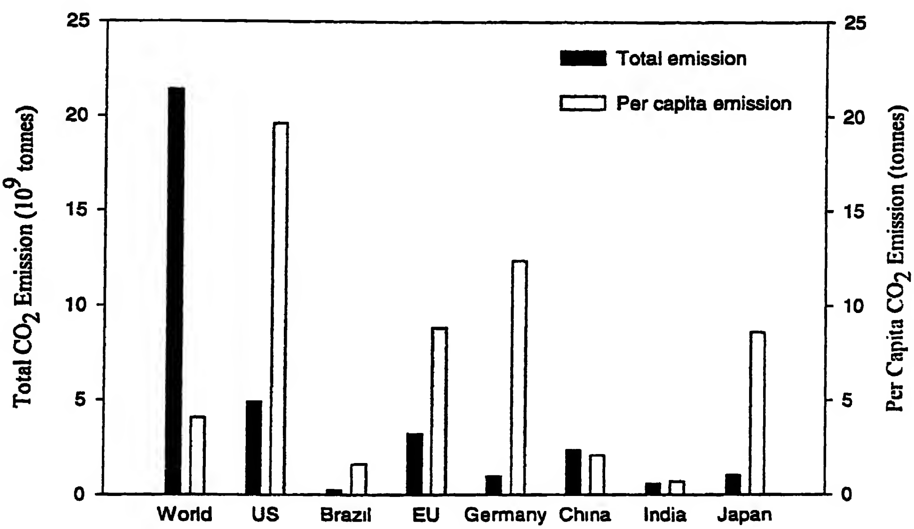

Fig. 11. Total and per capita CO_2 emission from fuel in 1990 for different countries.

Table V: *Countries which have Ratified Kyoto Protocol as on January 13, 2000*

Antigua and Barbados	Maladives
Bahamas	Micronesia
Bolivia	Mongolia
Cyprus	Nicaragua
Ecuador	Niue
El Salvador	Palau
Fiji	Panama
Georgia	Paraguay
Guatemala	Trinidad & Tobago
Jamaica	Turkmenistan
	Tuvalu

There could also be practical limitations in curbing the emissions by some of the countries. Some estimates show that 2010, US carbon emissions are likely to increase by 34% from the 1990 levels in the absence of any change in use pattern. It is also argued that there is no participation of the developing nations. World population is expected to be about 7 billion by 2010 of which about 80% are expected to be living in the developing countries. Fig. 11 shows that per capita CO_2 emission from China and India in 1990 were only 2.1 and 0.7 tonnes of CO_2 respectively as against 19.6 tonnes of CO_2 of US and about 8.8 tonnes of CO_2 of EU and also that of Japan. In terms of electric power consumption, India's per capita share is only 300 kWh, while those of developed countries it is about 8500kWh and that of China about 600kWh.

The problem of the global warming is similar to the problem of ozone depletion but it was on a shorter time scale. CFCs and other trace gases were recognised As the potential ozone depleting substance in early 1970s. In the mid 1980s, ozone 'hole' over the Antarctic region was discovered. The international community took step immediately and a schedule for phasing out the production of CFCs was agreed and the Montreal Protocol was signed in 1987. It was later amended several times to make the phase out schedule faster. We know now that atmospheric abundances of main CFCs are showing decline or at least not growing[5-7].

SUMMARY

Based on extensive observations it is conclusively found that the concentrations of greenhouse gases are increasing. These increases in CO_2 and CH_4 are much beyond the natural variations observed from the ice core data for the past 4,20,000 years[11]. The climate has changed over the past century and is expected to continue to change. The balance of evidence suggests a discernible human influence on the global climate[5]. It has been agreed to protect the climate. The main objective of the UNFCCC is to stabilize the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The Kyoto Protocol has initiated a process to control these emissions and it aims to cut the emissions of greenhouse gases by 38 developed countries by an Average of 5.2% from their 1990 level by 2008-2012 period. There are no emission limits for the developing countries since their per capita emisions are much smaller than those of the developing countries since their per capita emissions are much smaller than those of the developed countries. However, in the next few decades, their total emissions will also be significant. The short-term target adopted at Kyoto avoids the issue of stabilizing concentrations. The reductions outlined in the Kyoto protocol would not prevent total global greenhouse emissions from rising. According to one climate model, even if all developed countries limit their emissions as per the Kyoto Protocol, the world temperature would still rise by about 2.1 °C by 2100. This is only

0.27° C lower than the 'business as usual' scenario of world temperature rise if no intervention is taken. This indicates that there is a need to control and cut emissions of greenhouse gases even beyond the limits specified by the Kyoto Protocol and also by the developing nations (like China, India, Brazil) through use of more efficient energy sources, efficient power geneation and by adopting renewable energy sources. Hydrocarbon gases are the most efficient for energy production and emit least CO_2. The conversion of hydrogen in hydrocarbon fuels accounts for most of their energy yield since hydrogen(H) produces about four times as much energy as per unit carbon (C). Wood weighs heavily with ten effective Cs for each hydrogen. Coal approaches parity with one or two H per C and a molecule of natural gas like methane has four H per C. The action needed to address climate change will be impossible to accomplish unless the public is made aware of the need and persuaded to take part in limiting the emissions. This is difficult because the effects of climate change lie decades ahead but controls are needed now.

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Renewable Energy Sources : Role of Solar Photovoltaics

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INTRODUCTION

Various energy sources power the engine of economic growth of mankind. Indeed, quality of life is a question of power and there exists a direct correlation between the gross national product (GNP) and the energy consumptionper capita in a nation. The relationship between energy consumption per capita and the human development index (which taken into account GNP, health and education levels) is very instructive and is shown in Fig. 1. It suggests that with a small increase in the energy consumption, the underdeveloped and developing nations will be able to increase the development index significantly. Unfortunately, such nations are perennially short of energy and the gap between the energy demand and supply continues to

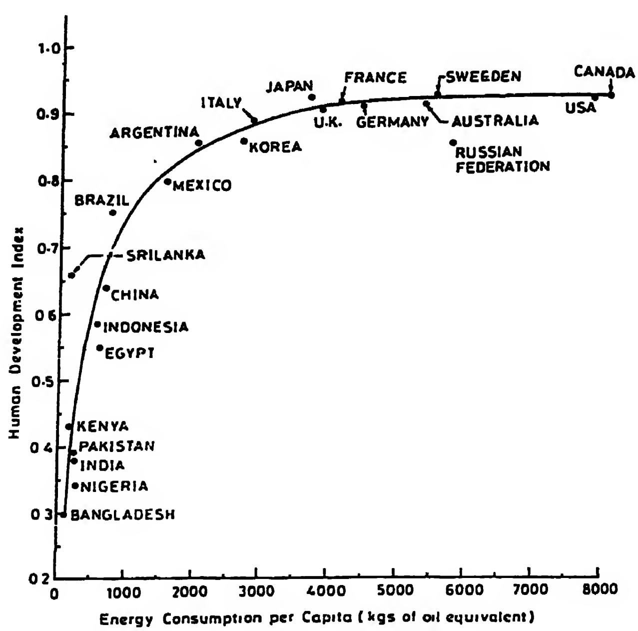

Fig. 1. Variation of Human Development Index with energy consumed per capita in different countries (Courtesy : Prof. H.P. Garg).

increase. For example, the electrical energy generated annually in India today is about 90,000 MW with-20% peak demand shortage and an annual overall shortfall of 8% or more.

WHY RENEWABLES ?

Fossil fuels are the major source of conventional energy in most countries. Besides being depleted rapidly, such fuels contribute significantly to the pollution and green house CO_2 gas emissions. It is estimated by the US Department of Energy that during 1996 these sources contributed 22 billion metric tonnes of CO_2 worldwide. Concerned with such consequences as also with national energy security, most nations have started serious search for alternative, preferably renewable and sustainable, sources of energy. Renewable resources of interest are : Solar; Biomass; Wind; Hydro; Ocean; Geothermal; Wastes. The energy potential of these resources is enormous. The potential estimated for India by the Ministry of Non-conventional Energy Sources (MNES) is :

Solar	20 MW/km^2
Wind	20,000 MW
Biomass	17,000 MW
Small Hydro	10,000 MW
Ocean Thermal	50,000 MW
Wastes	1700 MW

The contributions of Renewables to the energy resources vary considerably form country to country. As per US Department of Energy statistics of 1997, Renewables for year 1997 constitute only 8% of consumption, inUSA and are a mixture of hydro (55%) bio-fuels (38%), wind (1%), solar (1%) and geotherm (5%). In India, the installed capacity (in MW) on March 1999 as given by MNES is :

Hydro	22438
Thermal (coal, gas and diesel)	67618
Nuclear	1840
Wind	966
PV	2

It needs to be stressed that besides providing sustainable substitutes for depleting conventional fossil fuels to bridge the demand-supply gap, Renewables offer other notable features such as :-

- Abundant.
- Declining cost of renewables versus rising cost of conventional energy sources.

- GREEN (Generation and Resource Enhancement of Environment and Nature) technologies.
- Reduction of pollutants (for example, 1000kWh of photovoltaic energy helps reduce 8 pounds of SO_2, 5 pounds of NO, and 1400 pounds of CO_2 emission from a coal based thermal energy plant).
- Modular, variable size, and low gestation period technologies.
- Stand-alone economically viable systems for remote, inaccessible and grid-less area.

The technologies and the related economics of Renewables are continuously undergoing changes and improvements. The present day electrical energy conversion efficiencies and the cost have been estimated by numerous researches. The ball park numbers are listed in Table I, along with data onfossil and nuclear fuels for comparison.

Table I. Efficiency and Estimated Cost of Generation of Electricity from Different Sources (compiled from literature).

Source	Efficiency %	Estimated Cost Cents/kWh
Fossile Fuels	40-60	4-8
Hydro	30-50	2-10
Nuclear	?	4-12
Wind	15-30	5-12
Biomass	15-30	5-15
Ocean Wave	?	10-20
OceanTidal	?	10-20
Solar Thermal	15-30	15-40
Solar Photovoltaic	10-15	25-50

PHOTOVOLTAICS

Among the Renewables, solar energy has attracted much attention. Despite the large spatial and temporal variations of this rather dilute source of energy, solar energy is abundant and free. And, ironically, the developing countries which need energy sources the most of which are endowed with it generously. Solar energy can be converted directly into heat, chemical and/or electrochemical energy, bio-fuels, electricity etc. The direct conversion of solar energy into "dc" current and voltage with the help of a device called solar cell is termed as solar photovoltaics (SPV or PV.)

A solar cell basically consists of two electronically dissimilar regions of the same or different materials which create an electrostatic potential barrier at the junction. One may create such a junction in the same semiconducting material

(homojunction), two different materials (hetero junction), metal-semiconductor interface (Schottky barrier), metal-insulator-semiconductor, etc. A suitable material for solar cells must absorb solar spectrum efficiently to create electron-hole pairs which may be separated by the internal field in the junction area. The ultimate efficiency of conversion depends on the effectiveness of the processes of generation, diffusion, separation and collection of charges, and thus the optoelectronic properties of the materials and the junction characteristics. An ideal homojunction is expected to yield ~ 26% efficiency of conversion. An optimally designed heterojunction may yield ~ 40% efficiency. Due to limited solar absorption by any material with a well-defined band gap, higher conversion efficiencies are possible to achieve by exploiting either multi junctions or by two cells in tandem. In principle, as many as 36 suitable graded band gap junctions in tandem can yield upto 70% efficiency. But, such complex cells are of little commercial interest.

WHY PHOTOVOLTAICS ?

A solar cell is a battery of constant voltage (determined by the potential barrier at the junction) with current proportional to the intensity of light of suitable energy. One may string these cells in any flexible series and parallel combinations to yield modules of desired voltage and current ratings. Notable features of PV systems are:

- GREEN, sustainable and pollution-free technology.
- Conversion of global solar light by flat plate PV.
- Minimal maintenance since no moving parts are involved.
- Portable and easily assembled at any place in a short time.
- Flexible and modular to yield a power system of any specified power ratings.
- Compatible and integratable with any other power sources.
- Remote monitoring and control feasible.
- Long life for solar cells.
- Recyclable materials.
- Large specific power per unit weight, particularly in case of thin film solar cells.
- Ideally suited for small stand-alone power systems particularly in remote and grid-less areas.
- Talking life cycle costs into account, PV is economically viable as also a more favourable solutions for many small/medium power applications.
- As a sun-rise energy production and distribution industry, it is expected to be a significant driver of world economies and generator of jobs.

SOLAR CELL MATERIALS & TECHNOLOGY

Silicon : Ideally, a solar cell material should have a band-gap of ~ 1.5eV, high solar absorption coefficient (> 10^4/cm), high quantum efficiency, long diffusion length and long life time of charge carriers, and low recombination velocity. It should be cheap material-wise and energy input-wise, *n* and *p* dopable, available in different shapes/sizes in single crystal (sc) and/or multicrystalline (mc) form. Silicon satisfies some of those criteria. Though by no means ideal, being the best known and studied technological material, Si based PV technologies are the natural choice.

A block diagram of the various process steps for c-Si PV technology is shown in Fig. 2. Extensive research has led to numerous innovations. These include : (1) improved crystal growth techniques; (2) increased (upto 150cm diameter) water size; (3) more effective wafering techniques to minimize loss of material; (4) use of smaller wafter thickness down to 200μm; (5) provision of back surface field to enhance collection; (6) efficient AR coating; (7) creation of photon of photon trapping surface

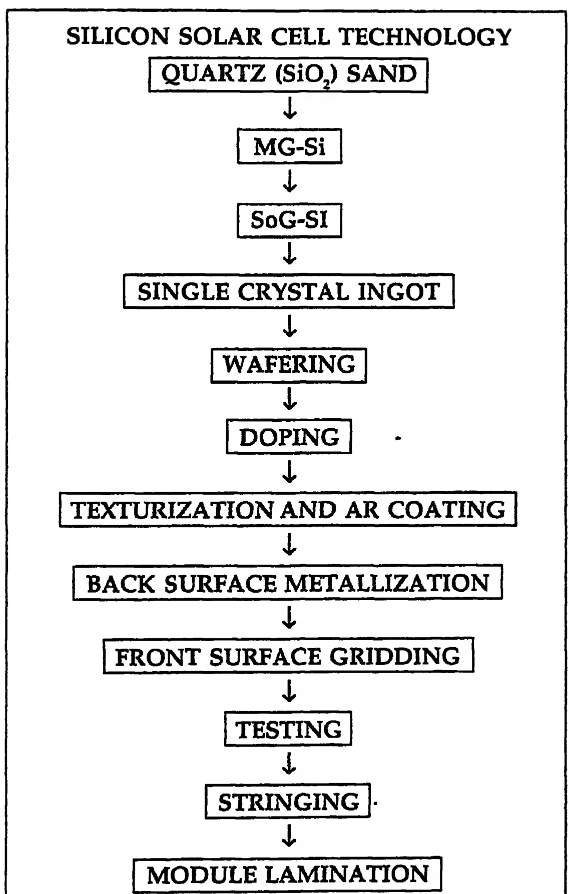

Fig. 2. Block diagram of the processing steps for c-Si PV technology.

morphologies; (8) effective and epitomized grid design; (9) innovative cell active region design; and (10) novel surface and defect passivation techniques. As a result, the efficiency of sc-Si cells has increased steadily for laboratory, pilot plant and commercial scales as seen in Table II. The highest efficiency obtained in a laboratory cell is 24.6% which is a remarkable achievement and it is close to the theoretical value. Megawatt scale production at 14-15% efficiencies is now common place. The cell reliability and life has increased at 14-15% efficiencies is now common place.

Under very special structured surface morphology processing and cell design conditions, limited production of 18% cells has been achieved by some companies. However, due to increased number of production steps and precise surface machining by lithographic processes, such a technology is expensive and not suited for large scale manufacturing.

Figure 3 shows the rapid growth of c-Si based PV production and concomitant decrease in the production cost which has leveled to about $2 per peak watt (Wp). Efforts have been made to cut down the energy budget as also the production costs by using lower purity grade Si in the form of cast/melt spun mcsheets/ribbons, with appropriate grain boundary passivation techniques. Although reasonably high efficiencies have been obtained (Table II), and mc-Si has a good market share (Table III) high stability and long life for cells remains a question mark. The overall cost of mc-Si based PV is not significantly lower than that of sc-Si at present though serious efforts continue to achieve the goal of $2/Wp or less.

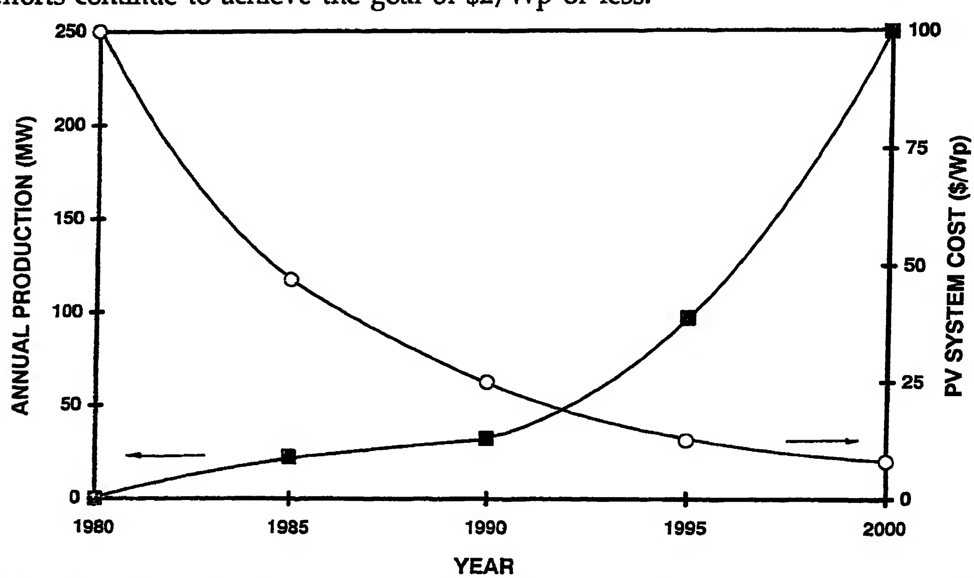

Fig. 3. World Silicon-based PV production (in MW) and cost of the PV systems from year 1986 to 2010 (compiled from published literature).

Table II. The Progress of Best Efficiencies of Laboratory Cell (L), Pilot Type (P) and Commercial (C) Modules Over Years and Projected to Year 2010.

Cell	FY 1919			FY 1995			FY 1998			FY 2000			FY 2010		
	C	P	L	C	P	L	C	P	L	C	P	L	C	P	L
Fossile Fuels	13	17	23.1	15	21.6	24	15	22	25	16	22	25	18	23	26
Si Film	–	–	–	–	10	12	–	12	14	–	14	16	–	16	18
A-Si Single/	4	6	9	9	8	10	7.8	9	12	9	10	13	10	12	15
CIS	–	9	13	7-9	10.2	17.1	11.8	13	18.8	12	14	20	14	16	20
CdTe	–	6	12.5	6	8.4	15.8	9.2	10	15	10	12	18	14	16	20

Table III. Percentage Share of Crystalline, Multicrystalline and Amorphous Silicon Cells in World PV Market (from Ref. 4)

Cell ↓ Y →	1986	1988	1990	1992	1994	1996	1998
c-Si	45	40	36	36	50	52	50
m-Si	15	20	34	38	34	36	42
a-Si	40	40	30	26	16	12	8

THIN FILM PHOTOVOLTAICS

There is ageneral recognition that the only way to cut down PV cost below \$2/Watt is to develop thin film PV systems. Thin film of suitable semiconductors with high optical absorption in the visible offer numerous advantages such as : (1) Tailorability of a number of relevant optical, electrical and opto-electronic properties; (2) Small thickness (typically ~ few micrometers) and thus very little semiconducting material needed; (3) Choice of a number of PVD, CVD, ECD and hybrid deposition techniques; (4) Very large surface area by a batch or continuous process feasible; (5) Choice of a variety of thin, cheap and flexible substrates; (6) Monolithic integration of cells to form modules during processing; (7) Large scale monolithic manufacturing with substrate in, encapsulated module-out feasibility; (8) very high specific power per unit weight on substrates of desired shape and geometry.

The manufacturing unit process for thin-film PV, irrespective of the cell material consists of the following steps: (1) preparation of a suitable substrate of appropriate dimensions; (2) cleaning; (3) deposition of conducting (in some cases transparent and conducting) contacts onto the substrate; (4) deposition of the junction forming semiconductor film of desired thickness by an appropriate technique; (5) deposition of conducting contacts; (6) mechanical/laser scribing at different stages of the manufacturing process to achieve monolithic integration; (7) encapsulation; and finally (8) external electrical connection.

A large variety of thin-films are suitable for cell applications. Starting with elemental Si films, binaries such as Cu_2S, CdTe, GaAs, InP, InP hydrogenated amorphous silicon (*a*-Si:H) and ternaries such as Cu-In-S Cu-In-se (CIS) based have

been the focus of much R/D work. In principle, the tailored multinaries offer an unlimited choice. But, the more complex the material the more difficult it is to manufacture economically as well as reliably. Of course, research continues on other possible thin-film materials such as fullerenes, diamond, copper oxide, some organic compounds, etc. We will confine our discussion to Si, *a*-Si:H CdTe and CIS based materials which are competing intensely with each other.

Analysis of production costs for the various thin-film materials and associated technologies has been carried out by various organisations notably NREL (USA). The major material and energy costs for manufacturing are determined primarily by the substrate and atleast one of the dominantly expensive component such as Ge, Ga, Te, In, Ag etc. used in the cell fabrication. Although metallic foils, ceramics, and plastics (e.g. Kapton) have been used for some thin-film PV, glass substrate coated with a transparent conducting oxide film is the preferred choice due to its processability, ready availability, and reasonable cost. Further, although the energy cost and the material use efficiency do vary considerably for different deposition processes, the overall cost of production keeping all parameters in mind comes out to by roughly the same for all cell technologies. As an example, Table IV lists the projected costs of CdTe thin-film solar cells for 20 MW plant being set up by the First Solar Company in USA. For large scale manufacturing the cell production cost for different cells ranges from $0.5 to 1.0/Wp and the Energy-Pay Back period varies from a few months to a year.

The physics and manufacturing technology of thin-film solar cells was pioneered by the very first Cu_2S/CdS cell. Although laboratory efficiencies ~ 10% and production process efficiencies - 6% were obtained, the cell was abandoned partly because of poor stability and partly because of the more reliable c-Si PV technology.

The discovery that hydrogenated amorphous silicon (*a*-Si:H) films produced by glow discharge (GD) decomposition of $Si:H_4$ can be doped *n* and *p* led to an exciting era of intense R/D activity on the material and its associated *n-i-p* solar cell. The cell efficiency has increased steadily to ~9.3% for single junction and to 13% for triple junction (See Fig. 4). Several megawatt PV production plants have been setup indifferent countries. Since 1986, production of cells has been at the level of about 10 MW/year. Consequently, the percentage PV share of this very promising technology has declined steadily from 40 down to less than 10 (See Table IV).

The GD is a good and simple process for manufacturing *a*-Si:H cells. However, a rather low throughput due to low rate of deposition of device quality material, and the intrinsic Staeblar-Wronksi (SW) degradation effect are serious drawbacks. Serious R/D efforts to overcome both these problems have achieved limited success. By using ultra-thin intrinsic layer of *a*-Si:H and by creating multiple junctions, stability of the cells has been improved considerably but not completely. Stabilized efficiency modules of single and multiple junctions of efficiencies ~ 5 and ~7% respectively are

being manufactured. Although the rate of deposition can be increased by a factor of 10, its utility in providing device quality material and thus high quality, high efficiency cells manufacturing is doubtful. Mixed amorphous and nanocrystalline Si films offer other possibilities. Nevertheless, at present, the *a*-Si:H cells offer no cost advantage over the c-Si cells and thus are going to lose the battle of survival unless throughput, stability and efficiency problems are solved.

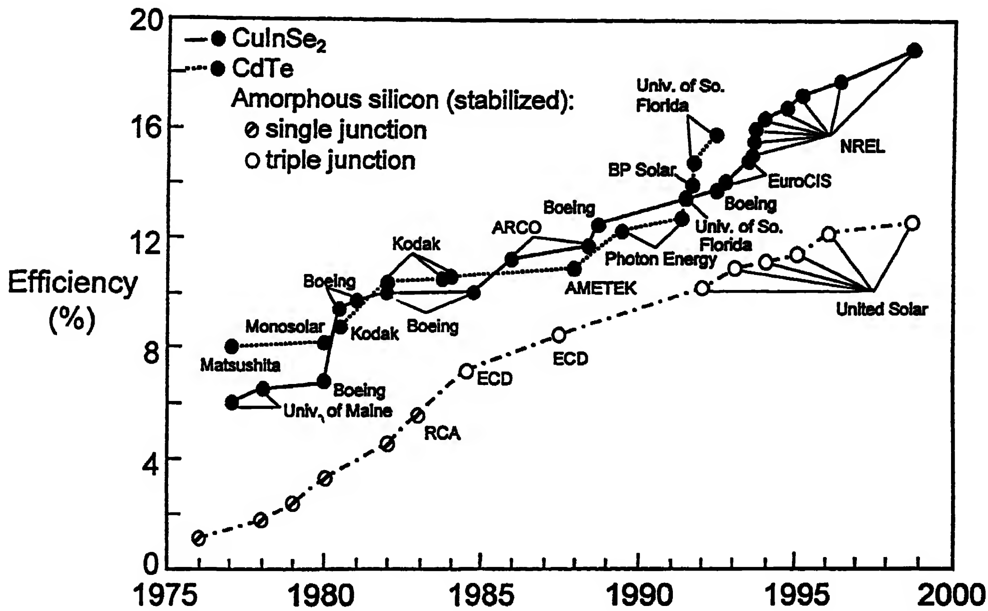

Fig. 4. Progress of record laboratory cell efficiencies for different thin-film technologies. (*Source* : NREL, USA; *Courtesy* : Dr. Harin Ullal)

Table IV. Summary of the Item-wise manufacturing Cost of CdTe Thin-film Solar Cells at 20 MW/Year as modelled by the Manufacturer taken "First Solar"

Component	Direct Manufacturing (Cost $/m^2)	Comments
Materials (all)	$48	Semiconductors only about $5 mostly encapsulation, substrate & modularization.
Capital (all)	$10	Semiconductors only about $5.
Heat, Electricity, Water	$3	Energy Payback < 3 Months for Energy Added during Manufacturing.
Labour	$12	Plant Labour and Operations Management.
Maintenance of Equipment	$3	4% of Initial Capital Cost
R&D	$4	Must Maintain Technical Lead.
Warranty	$5	3% of Sales (very high for eary high prices)
Rent and Factory Overhead	$5	Factory Overhead at 1.5% Sales.
Total Direct manufacturing	$90/m^2	Projected from Existing Technology,

Thin film CdTe/CdS cell is an ideal cell for large scale manufacturing by simple PVD, ECD, spray pyrolysis, or screen printing techniques. Considerable R/D on the CdTe cells and its manufacturability have been undertaken. As a result, the cell efficiency has reached ~ 15.8% as seen in Fig. 4. Several pilot plants of 10-100 kW scale have been operational for sometime. Some megawatt plants are in the planning/execution stages. Prototype modules ~ 5.8% efficient are available. Major issues which need to be resolved before large-scale production takes place are :-

- The process of *p-n* junction formation and the $CdCl_2$ treatment are empirical. In fact, the electronic nature of the junction itself is poorly understood.
- Achieving ohmic contact with p-type CdTe is more an art than science.
- The cell degradation is sensitive to device processing parameters and can be minimized to acceptable level with better understanding of the junction.
- Cd is perceived to be a toxic material. Recycling technology can be applied. However, public needs to be convinced that there are more serious Cd waste sources (e.g. Ni-Cd batteries, Coal) than envisaged with CdTe PV technology.

Thin film CIS (and its variants CIGS and CIGSS with additives of Ga and S) on CdS is a very interesting device despite its structural, optical, and electronic complexity inherent in a multi-component chalcogenide film. The cell is a champion in performance having reached 18.8% efficiency recently (Fig. 4) and has excellent stability. After a decade of prototyping, Siemens Solar has started limited commercial production of CIGs modules ~10% efficient. However, the cost of these modules is over two times of C-Si which means this technology is not yet ready to compete in the market.

Major issues in this case which need to be resolved are :

- Large area vacuum deposition of a multi-component semiconductor film, coupled with a selenization process to yield desired opto-electronic properties requires excellent and precise control which make the manufacturability of the cell a very difficult and expensive task. Although other deposition techniques have been tried out, PVD seems to be the best choice.
- The junction with CdS is sensitive to how CdS is deposited. The junction behaviour is not well understood. Nor is the correlation of the device performance with the microstructure and chemical composition clearly known.
- The availability of In and Ga for very large scale PV production is questionable at present.

The absence of a clear choice of a thin-film material and associated technology for viable manufacturing process has led to a renewed interest in polycrystalline (pc) Si films as an alternative. With innovative design of the cell enhanced optical trapping mechanisms, grain boundary passivation surface fields, it is possible to achieve high efficiency in thin (~20μm) films. Proof of the concepts has been demonstrated by achieving 10% efficiency in 2μm thick film cells. Major R/D efforts are expected to be mounted on technology for depositing thick pc/μc-si films at high rates (~1μm/min) over large areas. If it becomes a reality, pc-Si film will become a formidable competitor.

Table V lists the best efficiency thin-film, large area modules achieved by various commercial companies. A comparative analysis of various solar cells and technologies is given in Table VI. The technological maturity of the various technologies continues to move upwards. There is no simple way to evaluate this parameter is such a rapidly changing field. Nevertheless, a qualitative assessment is shown in Fig. 5 primarily to point out relative trends rather than absolute values.

Table V. Best Module Efficiencies as of Year 1998 as reported by Manufacturers of Different Types of Cells (compiled by NREL, USA)

Company	Material	Area (cm_2)	efficiency (%)	Power (W)
United Solar	*a*-Si Triple-Junction	9276	7.6	70.8
Solar Cells, Inc.	CdTe	6728	9.1	61.3
Solarex	*a*-Si Dual-Junction	7417	7.6	56.0
Siemens Solar	CIS	3651	11.8	43.0
BP Solar	CdTe	4540	8.4	38.2
United Solar	*a*-Si Triple-Junction	4519	7.9	35.7
Golden Photon	CdTe	336	9.2	31.0
Energy Conversion Devices	*a*-Si/A-Si/a-SiGe	3906	7.8	30.6

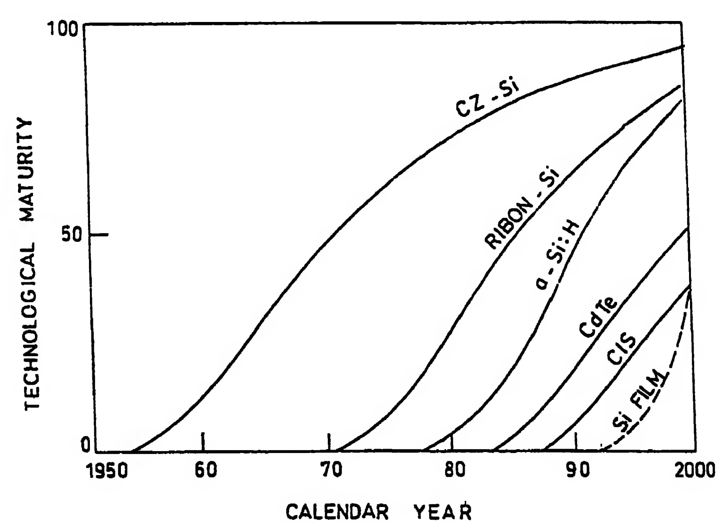

Fig. 5. Qualitative trend of the maturity level of the manufacturing technologies for various competing PV materials.

Table VI. Comparative Analysis of Different Features for the various Competing PV Technologies.

Cell Active Layer Thickness (mm)	Best Cell h (%) (Approx.)	Production Module h (%)	Life Stability	Production Technology Maturity	Production (1998)	ProductionCost ($/Watt)	Remarks
S-Si (SC/Poly) (300)	~ 24	12-15 (18% special)	> 20 yrs. Excellent	Cystal Growth Mature	~ 125	4	• Reliable • Cost Limitation
C-Si (Sheets/ Films) (20-50)	~ 12	~ 10 (Pilot)	Long Good	PVD & CVD Under Development	Panned ~ 1 MW	< 4	• Promising & Viable Needs further Development
A-Si:H (1)	~ 13	7-8 (Triple Jct)	Variable upto 5 years	GD Mature	~ 10 MW	4	• Long Range Commercial Viability Questionable • Instability and PoorThroughput Viability Questionable
CdTe (1)	~ 15.8	~ 9 (Pilot)	Fair Under Study	PVD & ECD Under Development	~ 20 kW	> 4	• Complex Production Process • Problems with Device & Process
Cu-In-Ga-Sa	~ 18.8	12 (Pilot)	Several Year Good	PVD & ECD Under Development	~ 20 kW	> 4	• Complex Production Process Viability Questionable
GaAs	~ 25	~ 12 (Pilot)	Several Years Good	MOCVD, MBE & LPE Mature	~ 10 kW	> 10	• Expensive • Good for Space Applications

FUTURE DEVELOPMENTS

It is universally accepted that c-Si based technology is the most mature one among the various options and thus is expected to continue to dominate the PV industry during the next one or more decades. Efforts, however, will continue to cut down the cost of manufacturing by employing simple production techniques such as (1) for grain boundary passivation; (2) Sol-gel based AR coatings; (3) Spinon, or screen printed coatings of materials for junction formation, back-surface field, and grid structure using Rapid Thermal Annealing and (4) Integration of processes for front and back electrodes. Further, techniques for casting c-Si into thin ($\leq 100\mu m$) sheets and for handling need be developed.

On the basis of the existing rate of growth of PV industry, US Department of Energy has projected module production level (in MW) as:

FY	MW
1997	125
2000	225
2005	580
2015	1500
2020	10000

If it is expected that over 80% of this production will be met by c-Si. To achieve this goal solar grade Si of over 150,000 MT will have to be produced. This calls for very large, megasize silicon plants to be set up. As to whether sc-Si will be replaced by mc-Si, the trend is indicated by the Japanese PV industry. During 1998, Japan produced 40 MW of PV, of which 70% was mc-Si. And, out of the 86% contribution of c-Si towards world PV production during 1998, a little more than half was based on mc-Si.

This film PV technologies will continue to be pursued vigorously. It will take some years before a clear choice between materials and technologies will emerge. In the meanwhile, healthy competition will continue and ultimately the cost manufacturing will be the final arbiter.

PV APPLICATIONS

No power means no development and thus zero watt costs a society a lot more than a watt. Consequently, remote areas where grid electricity does not exist, or it is too expensive to extend the grid, a reliable PV system is not only well suited but it is also economically viable. The same is true for replacement of small, stand-alone fuel (diesel, kerosene/petrol) generator sets with PV systems. The PV economics is even more attractive if life-cycle costs over the long life of the PV modules, and the ecological costs of the fuel generators to the society are taken into account. Thus, well established PV applications include : lanterns, home-lighting, remote area

telecommunications, railway signals, space satellites, cathodic protection for oil pipes, water pumping, emergency/strategic public facilities, etc.

Ranging from fractions of watts to several megawatts, stand-alone applications of PV systems are widely used world over. In developing countries, the emphasis is to provide for subsidized rural applications. As an example, India has installed PV systems of about 40MW in the field (as of 1998) for the following applications : Solar lanterns (2,45,000); Domestic lighting (95,000); Street lighting (38,000); PV Water pumps (4,500), Rural telecom power sources (1,90,000); Stand alone kW power plants (1MW); and interactive power plants (1MW). Several countries have announced very ambitious solar roof projects numbering in millions during the next few years.

With increasing PV production, larger PV plants for powering small scale industries for grid support, on for peak shaving applications are being experimented with by several Electricity Utility Companies. There are about 20 PV systems of over 0.5MW each capacity operating world-wide. The largest PV system operating today is a 10MW at Barstow, USA. Very large PV systems for serving industries or cities are not expected in the near future in view of serious manufacturing and cost constraints as of today.

Despite the obvious advantages, PV systems are not very popular and their sale is largely dependent on government subsidies worldover. Why PV is not market driven is due to a number of factors which include : (1) high cost; (2) poor public awareness and appreciation; (3) lack of ready availability; (4) lack of service and maintenance facilities; (5) tantalizing government subsidies and the associated barriers to innovation; and (6) lack of standardized products.

The high cost is a major road block. If, however, life-cycle-costs are considered, PV systems become economically viable for many applications. In any case, the module cost is going down. The Balance-of-System (BoS) cost which is comparable to the cost of modules cost must also come down correspondingly to reach less than $2/Watt. This would involve considerable RD efforts in developing cheaper storage batteries, inverters, power conditioning units and mechanical support structures. This neglected area is expected to receive a lot more attention in the future.

Once the PV products are freely available, reliable, maintainable, and reasonably priced, the public at large, in particular those who can afford it, will opt for this energy source. Its sustainability, it impact on reducing pollution, its role in making the user concerned about management and conservation of energy and the societal benefit in providing twice as many jobs per MW as compared with conventional sources will play a key role in driving the existing PV market of over 1.5 billion dollar involving about 2000 companies worldover to higher heights. Thus, PV is expected to usher in a Solar Revolution serving decentralized small and medium power applications.

CONCLUDING REMARKS

- With increasing worldwide concern for sustainable development, social costs, rising cost of hydrocarbon fuels, public sensitization of life-cycle-costs, the SPV energy sources will become commercially competitive with conventional sources of energy and will be market driven within the next two decades or so.
- Worldwide production of SPV is expected to cross 1000 MW annually around Year 2015 and will double thereafter every five years or less.
- Improved performance, reliability and reduced costs of balance-of-system components such as batteries, inverters, power conditioning unit, mechanical structures etc. will accelerate the growth of PV industry for applications ranging from small/medium size PV power stand-alone systems to megapower grid support and base power utility applications.
- As a sunrise industry, with 2000 SPV companies, with over 1.5 billion dollar turnover worldwide, the industry is expected to become a significant part of the environmentally friendly energy economies of many countries.
- Thinner ($< 2000\mu m$) single crystal/multicrystalline silicon sheet/wafer based solar cells with effective passivation, light trapping and antireflection properties and high performance junction design, yielding large area production scale efficiencies of 15% of better will dominate the SPV for the next couple of decades.
- Large scale production of silicon and > 10 MW solar cell production plants and other innovations are expected to bring down the cell cost to $ 1/Watt in due course.
- Thin film solar cells continue to hold the real promise of bringing down the cost of SPV below $ 1/Watt. The competing technologies are : a-Si:H based, CdTe and Cu-In-Se (CIS) based, and c-Si film. Tremendous amounts of R/D have been invested in these technologies. The progress in terms of efficiencies of laboratory cells is impressive. The cost of the cell and payback period for all these technologies are estimated for megawatt scale production to be comparable.
- Of the Thin Film Technologies, a-Si has been the most promising one leading with over 20MW production annually during the year 1980. With poor throughput in production, intrinsic instability in the cell and the overall cost being no advantage over present c-Si costs have led to its rapid decline.
- Despite high efficiencies and good stabilities achieved with CdTe and CIS cells in the laboratory and despite MW scale production plants in the process of being setup, the future remains uncertain due to the uncertainties in the unit

production processes involved. The c-Si films offer an attractive future if and when a viable production process is achieved.

- Which material and which technology will ultimately dominate remains a question mark. The clear choice(es) will no doubt be determined by the simplicity of cell design, and cost of manufacturing. Some cheaper materials and simple chemical technologies are expected to emerge after continued R/D for some decades to come.
- Being a limited energy source, SPV can never assume industrial energy role. Nevertheless, as sustainable and renewable energy source for small and medium scale stand-alone applications, particularly in remote and energyless areas (Remember: No Watt cowts more than a Watt), its societal role in providing job opportunities and in moulding an energy efficient and conservation mind set, SPV will play a very key and essential role in the economies of many countries.

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CAN INDIA FEED ITSELF ?

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NEED TO LOOK AHEAD

The Malthusian concern for the demand for food outstripping the limits of natural resources to provide the demanded food has time and again proved to be misplaced. Expansion of area under cultivation in the "new" continents, as well as through expansion of irrigation, progress of technology both in the manufacture of agro-chemicals and in the breeding of high-yielding varieties and innovations in the institutional arrangements to encourage farmers to produce more, have seen that the supply of food and agricultural products has kept pace with the growth of demand in the world. Furthermore, because of the unprecedented growth in populations and incomes, demands must have grown faster in this century than during any other period in human history. Even then, demands, certainly effective demands, have been met.

What then, one may ask, is the problem ? Why can't we continue to meet such demands in the future ? There are two reasons why Malthusian concern may be of some relevance today. First, the plausible growth rates in the coming decades of population and incomes require demands to grow at very rapid rates. Annual additions to productions in absolute as well as in percentage terms will be large. Will the rate of induced innovations be sufficient to meet these demands ? Second, the problem for India may be particularly relevant. A large country with 1/5th of the world population may not want to rely on the world market for something as elementary as food.

This discussion raises a number of questions. What will be the growth of demand for agricultural commodities arising out of populations and income growth over the first half of the 21st centuryin India ? Given the resource endowment, can India meet these demands ? This paper is addressed to these questions.

In other words, would India remain 'food secure' ?

FOOD SECURITY IS A PROBLEM OF THE POOR

The definition of food security elaborated at the World Food Summit is quite comprehensive. "Food security is a state in which all people have physical and *economic access,* for an active and healthy lie." (Emphasis added by author).

I would add that food should be provided to all as a matter of right without inflicting any humiliation on the poor. How this is accomplished, through the market mechanism or through government ration shops, is not fundamental to the notion of food security.

One has to note here that the operative world is economic access. With economic access i.e., enough purchasing power, other conditions get fulfilled in most normal situations. The present world food system normally functions efficiently at least in an economic but not a moral sense. It provides at reasonable prices adequate food of their choice to those who can afford to pay for it.

Thus food security is a problem of the poor, poor persons, poor households and poor countries. The hungry in the world are hungry because they are poor. They are poor because they own too little resources of land, capital or skills. There can also be a vicious circle. Due to lack of food the poor may not be physically and mentally productive enough to earn adequate income and thus remain poor. Nonetheless, hunger is primarily a problem of poverty and not of food production. Thus, if all the poor are given additional income, more food would be demanded and produced. But if more food is produced because farmers are given higher prices, the poor whose incomes have not changed, would continue to remain hungry. Thus, food security can be provided to an individual either by increasing his or her money income or by decreasing the price at which "adequate" food is made available.

Food security for a country is also a matter of poverty and underdevelopment. If it has enough income, it need not be self-sufficient. It can import the food it needs. But if it is poor and deficient in food production, it becomes more vulnerable to transient influences that reduce domestic production or increase world market prices.

Thus, lack of food security is a problem mainly for poor people and poor nations. While it is conceivable—for example, in some nuclear winter scenarios that the global food production falls so much below the demand that even the rich nations cannot find enough food supply, shortages are very unlikely. The technological food production potential of the world, even without invoking exotic technologies, is so large [Linnemann *et al.* (1979), Higgins *et al.* (1980)] that inability to produce food at any cost is not likely to threaten food security of the rich nations. Of course, even in a rich country, political, economic or natural disasters can disrupt food security. They may also thus follow policies to enhance their food security through bufferstocks, through minimum levels of self sufficiency, etc.

Food security is defined in terms of sufficient food. However, what constitutes sufficient or "adequate" food intake is still a matter of contention among nutritionists. Sukhatme (1978) pointed out the difficulties of defining this, noting that metabolic rates vary across similar (in height, weight, sex) individuals and also across time for

a given individual. Also individuals learn to live with less (or more) calories over time. Srinivasan (1981) provides an overview of these issues. Yet, no matter how one measures hunger and poverty, one finds that hundreds of millions of persons suffer from hunger and poverty [FAO (1991), World Bank (1986, 1990)] in the World. In spite of significant progress over the years, chronic undernutrition persists and continues to affect nearly 800 million persons: (See Table I).

Table I. Number and Percentage of Population Undernourished in the Developing Countries.

Region	Percentage of Population		Number of Undernourished (millions)	
	1979-81	1995-97	1979-81	1995-97
Sub-Saharan Africa	37	33	126	180
Near East and North Africa	9	9	22	33
East and Southeast Asia	29	13	406	240
South Asia	38	23	337	284
Latin America and Caibbean	13	11	46	53
All developing regions	**29**	**18**	**938**	**791**

Note: Numbers do not add up to the total because of the Oceania region
Source: The State of Food Insecurity in the World (SOFI). 1999, FAO, Rome.

The poverty line in India is defined on the basis of income needed to get 2100 kcal/cap/day in urban areas and 2400kcal/cap/day in rural India. Thus estimates of poverty can be taken to be an estimated of hunger. Figure 1 shows these estimates based on sample surveys carried out by the National Sample Survey Organisation (NSSO). One sees that even in the 90's 30 to 40 percent of the people are below the poverty line i.e., hungry.

The fact that at the same time we have 30 million tonnes of foodgrains in the government bufferstock proves the point that hunger is a problem of poverty.

In addition to the millions who suffer from persistent hunger, many others who normally get enough to eat live precariously on the margin of subsistence.They are vulnerable to external influences which can easily reduce their food consumption and make them join the ranks of the hungry. A major threat to the already inadequate food consumption of the poor is from a drop in real income.

Both persistent hunger and transient hunger, the extreme form of which is famine, have attracted analysts. First (Linnemann *et al.* 1979) with MOIRA and later Parikh and Tims (1986) and Fischer *et al.* (1991) with IIASA's BLS [Basic Linked System, Fischer *et al.* (1988)] have underlined that to deal with chronic hunger is to deal with poverty and underdevelopment.

Sen (1991) and Dreze and Sen (1989) have extensively examined how to deal with the extreme case of transient hunger namely, famine. It is relatively easy to deal with famines as usually, if the government of a country desires, much

international aid is available. Even then famines have led to large scale death since the World War II and the question is why don't governments take effective action in time to prevent deaths due to famine. Dreze and Sen stress the role that freedom of the press and media play in mobilizing timely and effective action. Figure 1 shows that year to year changes in percent below poverty line are large, sometimes exceeding 10 percentage points e.g., between 10^{th} and 11^{th} rounds. A change of 5 percentage points is common. Thus large number of persons turn from being non-poor to poor and vice-versa from year to year. The incidence of transient poverty is large.

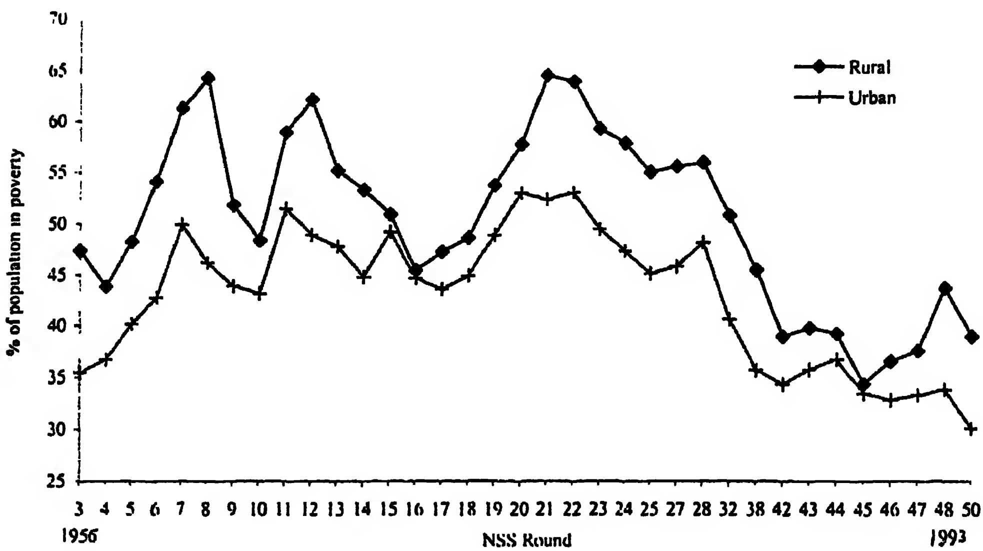

Fig. 1. Incidence of hunger in India-Head Count Ratio (HCR).

3. SUBJECTIVE HUNGER

Since calorie norms are controversial, one might wonder why not ask people directly if they get enough to it or not. This is what the NSSO did in two surveys, once in 1983 (calendar year) and again in 1993-94 (financial year). The results shown in Table II are dramatically different from traditional estimates of poverty for these years, Table III.

Table II. Subjective Hunger-Do you get Two Square Meals a day ?

	Percentage of Population			
	Rural		Urban	
	1983	1993-94	1983	1993-94
No	2.4	0.9	0.8	0.5
Only some months	16.2	4.6	5.6	1.4
Throughout the year	81.1	94.5	93.3	98.1

Table III. Measures of Poverty

Measure (Unit)	Rural 1983	Rural 1993-94	Urban 1983	Urban 1993-94
1. Head Count Ratio (HCR)[a] (%)	45.3	8.7	35.7	30
2. Poverty Gap[b] (percent)	12.7	9.4	9.5	7.6
3. Squared Poverty Gap[c]	4.8	3.3	3.6	2.8

[a]Percent of people below poverty line
[b]Income needed to bring the poor to poverty line as a percent of total national income.
[c]A nonlinearly weighted depth of poverty which gives greater weight to the more poor.

What is striking is that while subjective hunger has come down dramatically, the change in traditional measures is negligible. This may be because of increasing biases in measurement of traditional indicators, Parikh (2000). Why this is so however, will take us too far away from the main theme of this paper.

The point of all this is that hunger has come down significantly and the main problem is to provide purchasing power to the poor. While this may be true today, what about future ? How much do we want and would we be able to produce enough food to meet the demand ?

4. PROJECTING LONG TERM FOOD DEMAND APPROACHES

As India's economy grows at a rapid rate as is likely and as its population continues to grow, we should expect a rapid growth in food demand. One should also note that historically, international price of foodgrains have been coming down. In a liberal trade economy, domestic food process would follow international prices.

Thus, a richer and larger population would demand more food and price increase may not dampen that demand.

As a person becomes rich, he not only eats more, he eats different kinds of food. The pattern changes, Demand for some foods such as coarse cereals, falls as income rises. Such foods are called inferior goods and as replaced by superior goods whose demand rises at a faster pace than income. Milk, meats, vegetables and fruits are such goods.

The changing pattern requires that demand for all foods is better estimated simultaneously as a system so that they are internally consistent. Traditionally, economist requires that the expenditure on all different goods should equal the total income the consumer has to spend on these goods. Long term projections call for an additional consistency, namely of total calorie intake which should not exceed physiologically realistic levels. Figure 2 shows this.

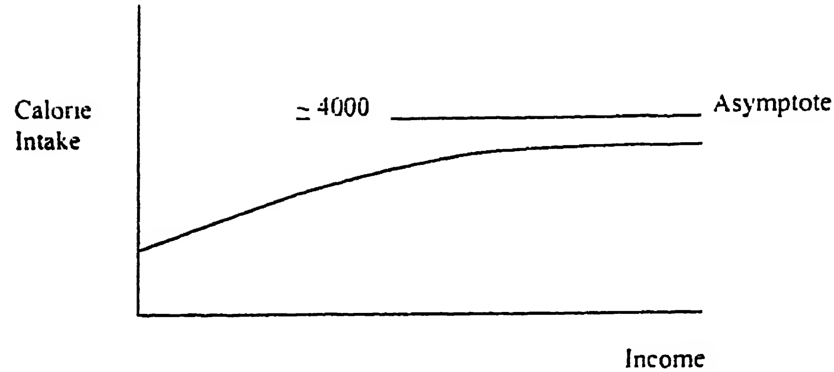

Fig. 2. Calorie Intake per Person/Day

Demand projections for a basket of commodities are traditionally made on the basis of a complete expenditure system. However, empirically estimated systems are mostly linear expenditure systems which are not appropriate for long term projections involving large changes in income and expenditures.

These difficulties, with projections made using different methods, are illustrated the *Appendix*. Here, only projections are given based onour preferred method described above.

5. LONG TERM FOOD DEMAND FOR INDIA

Two alternate scenarios of GDP growth and two of population growth are generated. However, I report the results of only the two extreme scenarios as they bound the projections. These scenarios are as follows :-

MP-LG : Medium population growth and low GDP growth.

HP-LG : High population growth and high GDP growth.

The assumed growth rates are given in Table IV.

Table IV. Assumed Growth Rates of GDP and Projected Population.

	Projected Population at end of period (millions)		Annual growth Rate of GDP	
	High	Medium	High	Low
2000-2020	1390	1345	7.15	3.87
2020-2050	1710	1646	4.75	2.75

The projected food demands for human consumption are shown in Table V.

Table V. Human Consumption Demands for India for 2020 and 2050

	Units	MP-Lg		HP-HG	
		2020	2050	2020	2050
Wheat	Million tonnes	65.3	118.3	100.3	192.1
Rice	Million tonnes	96.8	125.8	109.0	179.2
Coarse Grains	Million tonnes	26.6	30.0	26.0	39.2
Cereal total	Million tonnes	188.6	274.1	235.2	410.4
Oils fats	Million tonnes oil equiv	8.8	16.7	14.1	35.6
P. feeds	Million tonnes Prot. Equiv	1.1	2.1	1.7	4.1
Sugar	Million tonnes sugar refine. Equiv	34.7	58.4	49.5	101.6
Bov. Ov. Meat	Million tonnes Protein Equiv	6.6	12.7	1.06	34.7
Pork	Million tonnes Carcass Wt.	0.7	1.8	1.5	5.2
Poultry	Million tonnes Prot. Equiv.	0.1	1.8	1.5	5.2
Dairy	Million tonnes Wh. Milk Equiv	63.1	125.0	105.3	237.9
Fish	Million tonnes Prot. Equiv.	1.0	1.7	1.5	3.2

These are compared with the recently available projection by Bhalla *et al.* In Table VI for comparable items.

Table VI. *Comparison with IFPRI Projection for 2020.*

	Parikh HP-HG	IFPRI-Bhalla *et al.*	
Growth Rate % per year	7.1	≤ 6	8
Cereals (10^n tonnes)	235	246	267
Milk (10^n T)	105	290	164 (1.333) kg/person/day)
Meat, Pork, Poultry (10^n Protein Equiv.)	25		
Meat and Eggs (10^n T)		20	32
Foodgrains (10^nT)	40	50	107

It may be seen that even with a higher growth rate of GDP, I get lower demands for cereals, higher demand for meats and much lower demand for milk. Compared to IFPRI's lower projections. However, the differences are particularly large for Milk. The foodgrains required are not that different. It is worth noting that IFPRI's higher projection given a per capita consumption of milk which is higher than present US competition.

Long term projections are full of uncertainty and we should take these as ball-park figures.

The question now arises, 'can we feed ourselves ? Before we turn to it, I want to reiterate that there is no compulsion that we must grow all our foods ourselves. We can trade with other countries and as long as we have adequate money, they will supply us food.

6. FEEDING OURSELVES

Agricultural output over the past fifty years have effectively outpaced agricultural demand and one would think that feeding ourselves in future should pose no problem. Pessimists however, point to a number of problems :-

→ The growth rate of yield is coming down.

→ Land degradation is widespread and increasing.

→ How would climate change affect India's agriculture ?

→ Would we follow the needed policy ?

→ Let us examine these in turn.

Table VII shows the production of selected agricultural produce over the last five decares.

Table VII. Production of Agricultural Produce (in Million Tonnes)

Commodities	1950-51	1970-71	1980-81	1990-91	1996-97	1997-98
Rice	20.58	42.22	53.63	74.29	81.31	82.12
Wheat	6.46	23.83	36.31	55.14	69.27	66.05
Coarse Cereals	15.38	30.55	29.02	32.70	34.28	31.05
Pulses	8.41	11.82	10.63	14.26	14.46	13.35
Foodgrains	50.82	108.42	129.59	176.39	199.32	193.12
Oilseeds	5.16	9.63	9.37	18.61	24.96	22.24
Sugarcane	57.16	126.37	154.25	241.25	277.25	262.19
Cotton@	3.04	4.76	7.01	9.84	14.25	11.15
Milk	17.00	22.00	31.60	53.90	68.30	70.50
Eggs @@	1.83	6.17	10.06	21.10	27.50	28.42
Fish	0.75	1.76	24.4	38.4	53.5	53.9

@ Million Bales of 170kgs each.
@@ Billion number.

We can see the tremendous progress we have made and if we can keep production growing at the same rate, we should feed ourselves well.

7.1 DECELERATING YIELD GROWTH

Table VIII shows how production has grown and what have been the contributions of area expansion and productivity increases. The scope for expansionof area is limited as there is virtually no possibility of increasing net sown area and only possibility is to increase double cropping which requires expanding irrigation. Thus, the slow down in yield growth in the 90s compared to the 80s is trobulesome. We see in Table VIII that this has happened for for rice, wheat, coarse, grain, pulses, sugarcane, cotton and non-food crops, i.e., all crops shown in Table VIII show this.

This can be explained in a number of ways. Firstly, the growth rate of irrigation has slowed down. Secondly, may be the agricultural research system has not

performed as well in the 90s and the high yield varieties are losingvigour. Finally output and input prices do not provide farmers incentive to produce more. Form a long term point of view, the important question is, is there adequate irrigation potential in the country ? It is seen from Table IX that much irrigation potential still remains to be developed. I would also like to point out that at present water is highly subsidized. Much water is thus wasted. Drip irrigation for crops where it is feasible, is shown to use 30 to 50 percent less water per hectare and increase the yield. Thus, much scope exists to expand irrigation even beyond the official ultimate irrigation potential (UP) shown in Table IX.

Table VIII. Annual Compound Growth of Crop Area, Production and Productivity.

	1949-50 to 1965-65			1967-68 to 1996-97			1979-80 to 1989-90			1989-90 to 1996-97		
Crop	A	P	Y	A	P	Y	A	P	Y	A	P	Y
Rice	1.21	3.50	2.25	0.63	2.86	2.20	0.45	4.29	3.82	0.28	1.50	1.22
Wheat	2.60	3.98	1.27	1.52	4.68	3.11	0.57	4.25	3.65	3.16	2.63	2.73
Coarse Cereals	0.90	2.25	1.23	-1.33	0.61	1.91	-1.19	0.74	1.84	-2.46	- 0.52	1.69
Total Cereals	1.26	3.21	1.77	0.01	2.89	2.41	-0.16	3.63	3.43	-0.38	1.97	1.76
Pulses	1.72	1.41	0.18	0.16	0.94	0.76	0.15	2.76	2.63	-0.61	0.66	0.96
Food-grains	1.35	2.82	1.36	0.04	2.62	2.19	-0.11	3.54	3.33	-0.42	1.82	1.69
Oilseeds	2.67	3.20	0.30	1.38	3.64	1.75	1.45	5.41	2.73	2.10	4.58	2.52
Sugar-cane	3.28	4.26	0.95	1.77	3.12	1.33	1.89	3.73	1.81	2.30	4.17	1.65
Cotton	2.47	4.55	2.04	0.99	2.89	2.80	-1.32	2.19	3.56	2.67	4.17	1.46
Non-food crops	2.44	3.74	0.89	1.40	3.37	1.77	1.21	4.02	2.47	1.97	4.06	1.81
All Crops	1.58	3.15	1.21	0.38	2.91	2.01	0.21	3.72	2.99	0.24	2.75	1.72

A—Area : P—Production : Y—Yield

Source : Estimates of Area and Production of Principal Crops in India, Various issues, Directorate of Economics & Statistics, Ministry of Agriculture, Govt. of India.

Table IX. Region-wise Status of Irrigation Development in India

Region	Total Cultivable Area	Total Ultimate Irrigation Potential	U.I.P. as % of Total cultivate area	Percentage of Achievement March'97 Wrt U.I.P. (Utilization)
	(000'ha)	(000'ha)	%	%
Easterm	24990	29138	1166	46.32
North-Eastern	6340	4246	66.97	23.23
Northern	56381	47817	84.81	88.3
Southern	39531	25445	64.37	51.84
U.Ts	208	188	90.38	60.29
Grand Total	183956	139937	76.07	57.7

Source : Ninth Five Year Plan, 1997-2002. Draft.

Apart from the slight slow down in irrigation Expansion over the 90s, the fall in growth rate of yield can be expected for other reason as well.

As seen in Figure 3, when a farm shifts of a High Yielding Variety (HYV) he gains a big boost in yield from Y_0 to Y_1. Once he has made transition to a HYV, subsequent yield increases have to come from input intensification, where diminishing marginal product would slow down yield increases. When more and more farmers shift to high yielding variety, the growth rate of yield can be very high. But once all the farmers have adopted high yielding variety then to create higher yield, more inputs are needed. It slows down the growth rate.

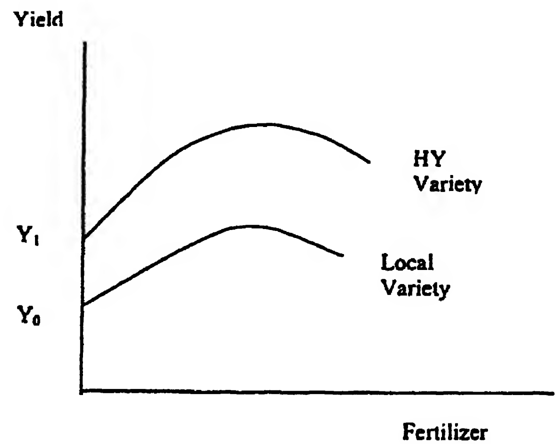

Fig. 3. HYV and Local Varieties

Moreover, HYV loses vigour with time. Newer varieties have to be developed periodically to compensate expand production possibilities. Experience has shown that this is possible to do. It greatly diminishes the importance of decreasing returns. Agricultural researchers in the US have periodically Expanded production potential for maize and wheat. Spring wheat varieties introduced at different time in the US, but all tested in 1974 to eliminate impact of variations in weather, soil and culture practices show (See Tisdale *et al.* 1985) that compared to the yield of variety available in 1926 yields were higher by 10% for the 1935 variety, 16% for the 1958 variety, 35% for the 1967 variety and 79% for the 1971 variety. Similarly, increasing yields with newer varieties were also observed for corn. See figure 4.

Also, the lack of success of our research establishment in introducing HYVs for the relatively drier regions and crops is a mater of concern. It is possible that this is in spite of an excellent programme and reasonable effort, for this is a difficult task. Yet, an evaluation of the efforts is required.

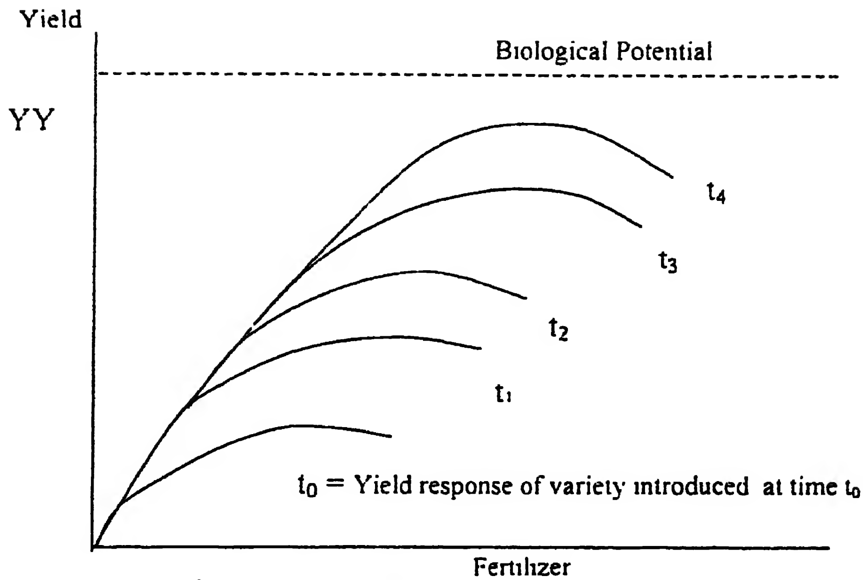

Fig. 4. Short Sun and Long Run yield Responses.

With a vigorous research Establishment, we should be able to keep increasing yields at the required rate, for the present yields in India are way below that what have been achieved in other countries.

7.2 LAND DEGRADATION

Many claim that much of India's land is degraded. This is usually claimed without specifying how degradation is measured. Land is privately owned by farmers. Why would an individual degrade her own property ? It does not make any economic sense. yet, it is possible that she is ignorant and does not know the impact of her actions. It is also possible that land is degraded by other people's actions. Yet, degradation of cultivated land seems not too likely. Of course, farmer may mine the land fertility in the short run and try to restore it later when he is richer. Such behaviour may be optimal from his point of view. Thus, loss of soil fertility is not likely to be a long problem. Unfortunately, data on degradation of cultivated land is not available. The detailed data of national soil surveys do not diffeentiate between cultivated and other lands. Thus, for example, the data for Rajasthan would include the Thar desert as part of degraded land.

A Ph.D. thesis by a student of the authors, Sudhir Sharma (1999) shows how the cultivation practices of Punjab farmers are rational even from a long term point of view. This is not to say that offers may not know what they are doing to their land. In the case of many pesticides that are being marketed today, the farmers do not really know the true nature of the things they are

getting. They are unaware of the adverse consequences for their health. At the same time, their may be a problem that their is no source of information on that. Only the trader, the representative of the pesticides company tells them about what it is about. So, we need to introduce a vigorous public information system which really tells farmer what are the advantages and dangers of using particular pesticides. Once he is informed, we can expect him to take a right decision.

However, action of many farmers, each acting rationally may lead to environmental degradation. Such is the case with over-exploitation of groundwater and the resulting lowering of water-table in many parts of the country. Equitable allocation of groundwater resources is required. However, it may be difficult to introduce at this stage community ownership of groundwater. Groundwater has been treated as an open access resource and only limited constraints on spacing of wells exist. A possible approach is to impose a cess on groundwater use leveied by the Panchayat to be used for land development and other community development programmes. Give this money to the Panchayats to spend on other social infrastructure. It can build school, hospitals, roads, drainage work etc. All these will help those who do not pump water. They will thus also get some share of the ground water they have. This will also increase the price of ground water and people will use it in a more sensible way. I think, we need to think in terms of these kinds of social mechanisms for certain community resources.

Finally, let me say something about the concerns for land degradation and sustainability of agriculture. Some people say that a large part of our land is degraded. By and large one would expect a farmer to know that land is his sole source of income. He would want to take care of the land as much as he could. Any rational person would want to preserve his productive asset in a proper way. So one would really expect that he would take care of his asset. In spite of that if he seems to degrade it, we should ask ourselves: is he really degrading it or is it a rational thing for him to do ?

7.3 CLIMATE CHANGE

Climate change can make significant changes in agricultural productivity in India. A Ph.D. thesis at IGIDR, Kumar Santha Kavi (1999), tried to assess these impacts. His scenarios look at some time in future, may be 100 years from now, when climate changes in specified ways. What would it mean for production, prices and incomes ? Table X summarizes these results.

Table X. *Climate Change Import on Indian Agriculture*

Scenario	Assumptions	Impact
Temperature rise of 2.5 °C to 4.9 °C	No carbon fertilization	→ Rice Yield goes down by 15 to 42% → Wheat Yield goes down by 25 to 55% → Agri. GDP declines by 2 to 4% → Food price increase by 7 to 18%
	With carbon fertilization	Similar but smaller effects
Temperature rise 2 °C and Precipitation increases by 7%	Farmers adapt	→ Farm incomes decline by 9%
Temperature rise 3.6 °C precipitation increases by 15%	Farmers adapt	→ Farm incomes decline by 25%

Based on Kumar, Santha Kavi (1999).

7.4 CONCLUSION ON PRODUCTION POSSIBILITY

Even the low trend growth rate of 1.97% per annum would be adequate to produce the cereals we need to 2020. With the irrigation potential that remains to be exploited, with the large inefficiency of water use that can be reduced at modest cost, with the yield potential gap the remains to be filled and with rational farmers who look after their land, we should have no difficulty in feeding ourselves long in the future.

What do we need todo to realize the potential ?

8. POLICIES FOR FOOD SECURITY

The most important policy goal should be rapid economic growth. That will also require strong agricultural growth.

Unlike Indian Industry, the Indian industry farmer has operated in a competitive environment. He is an efficient farmer i.e., given the prices he faces and given available resources, he optimizes his own consumption and income. (This cannot be said of our public sector managers.) Thus to increase agricultural output we must make it feasible and profitable for the farmer to do it.

The most important step is to liberalize agricultural sector and give farmers international price for output and inputs. This transition can be made over a period of 3 years. Farmers may have to be protected against short term fluctuations of international prices. Domestic price stability at the inernational trend rate may be maintained. This may be accomplished through a mix of domestic bufferstock and trade policy. All agricultural commodities should be put under Open General License (OGL). Export quotas on some commodities may be imposed and auctioned off. The quotas have to be consistent with stabilization objectives.

All domestic restrictions should be removed so that farmers can decide on the most appropriate allocation of their resources.

For farmes to obtain good prices for their products, marketing and transport infrastructure should be improved to minimize transaction costs. Good road, better infrastructure should be improved to minimize transaction costs. Better roads and communication facilities and organized markets improve the prices received by farmers. Governments should develop these.

To facilitate trade and open up new markets for the farmers, cold chains from farmgate to ports and airports need to be developed. Government has a role to play here.

To sustain agricultural growth, a regular flow of new seeds and technology is required as varieties lose vigour after some time. A vital research system that is creative, dynamic and responsive to changing needs and circumstances must be maintained. A public research system competing with private researchers should be adequately funded and so organized that creativity and success are rewarded. At the same time, it should not be a public monopoly and all obstructions against private research should be removed.

A mechanism to prepare strategic plans and research goals should be set up which involves the finest minds in the country from within and outside the government. The plan should set goals for different agro-climatic zones, soils and crops. It should balance probability of success against likely social pay-offs from alternative lines of research. The plan should also recognize the potential of biotechnology and information revolution. Otherwise, Indian farmers would lose their competitive edge against farmers in countries which exploit these potential. While exploiting the potential of biotechnology, we should regulate it to keep it safe, to maintain transparency through public information, to ensure consumers right to choose if she wants to consume such products or not, and to retain an ethical perspective that precludes "terminator" seed type greed.

This plan should really understand what are the options available and what is it that we should do. In Figure 5, we show four yield response curves. The first one shows the response of the actual cultivated variety and the cultivation technology used. Curve 2 represents the best available variety. Curves 3 and 4 working at point Y_1, point Y_2 reflects the economic optimum with the best available variety, whereas point Y_3 is a socially optimum level. We can say that the difference between Y_2 and Y_1 is an extension gap because with extension farmer should be producing At Y_2.

The difference between Y_3 and Y_2, on the other hand is a policy gap. With appropriate changes in policy, we could induce the farmer to produce at Y_3. Similarly, we define the research gap and the land development gap.

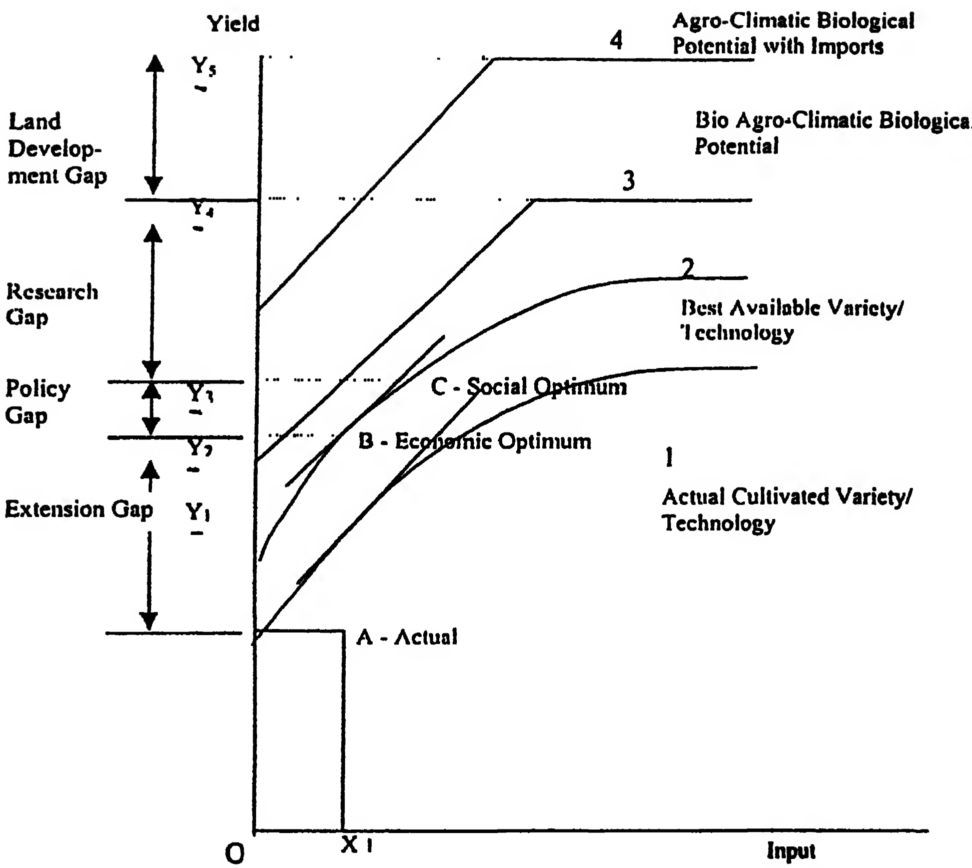

Fig. 5. Assessing Causes of Agricultural Backwardness

A systematic analysis of identifying the various gaps in different parts of the country should be done and then based on that we should work out a strategic development plan for each region and research strategy for it.

We should have a tremendous comparative advantage in research, including biotechnology. To fully exploit it, we should set up an appropriate regime of intellectual property rights (IPR) that also protects plant varieties, and farmer' rights. This should encourage private sector research but also benefit public sector researchers, if they are given opportunity to gain financially from their patents. A *sarkari* scientist should also have the right to profit from her research and there should be some kind of incentive given to scientists of IARI as well. A dominant public sector research establishment should protect farmers from possible exploitation by private sector researchers. And a vigorous private sector research would provide essential competition. Healthy competition would accelerate innovation.

CONCLUSION

Given the incentive of remunerative prices, a supportive infrastructure of irrigation, roads, markets and export facilities, a steady supply of new HYVs, Indian agriculture can be productive, vigorous sand competitive, able not only to face the challenge of a globalized world but thrive from it.

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APPENDIX

METHODS OF DEMAND PROJECTIONS

EXPENDITURE ELASTICITY-BASED PROJECTIONS

Commodity wise expenditure elasticities are often used for projecting commodity demands. This work uses the elasticities obtained from the reference run simulations of the basic linked system (BLS) of national models (Fischer *et al.* 1988) developed at IIASA, in a multinational research programme conducted by the author. Using these along with the projected per capita expenditure derived from the GDP and populations of section 2, we obtain the first set of projections. Assuming that aggregate savings rate would remain constant at the level projected for the year 2000 in the BLS scenario, we obtain per capita expenditure given the GDP and the population. The demand expenditure and

$$d_1 = d_0 \left(\frac{e_1}{e_0}\right)^{\eta}$$

elasticity are related as follows :

where d_1 = projected per capita demand;

d_0 = projected per capita demand;

e_1 = projected per capita expenditure;

e_0 = base year per capita expenditure;

and η = elasticity.

The expenditure elasticities, base year consumption level and projections are given in Table A-I.

These are very high demands and imply impossibly high calorie intake. For long term projections involving substantial growth in incomes/expenditures, commodity by commodity demand projections using elasticities are thus not satisfactory. One of the problems of such projections is that the implied expenditure for all the commodities does not add up to the total expenditure as they should. Therefore, we use a complete expenditure system to make a demand projection for India to see if the high calorie values inTable A-I were the result of not using a complete expenditure system.

Table A-I: *Annual Per Capita Human Consumption for India-Projections based on Income Elasticities*

	2000 Assumed Cons/Cap	Income Elasticity	INDIA 2050 C/CAP
GDP/CAP (USS$, 1970)	180.96		8.29
CALORIES/CAP/DAY	2526.38		5683.00
Weat	63.19	0.66	253.85
Rice	79.21	0.25	135.74
Coarse Grains	37.85	-0.21	24.17
Bovine & Ovine meat	1.31	0.17	1.89
Dairy Products	57.56	0.33	116.45
Other animal products	0.62	0.50	1.79
Protein feed	0.00	0.00	0.00
Other food	31.75	0.38	71.00
Nonfood agriculture	2.13	-0.31	1.12

Units Wheat, Rice, Coarse Grains - kg
Bovine and Ovine Meat - kg carcass weight
Dairy Products - kg whole milk equiv.
Other Animal Products - kg protein equivalent
Other Food. Non-food Agr.1970 US$

A Hierarchic Demand System Based Projection for India : We had estimated a 3-level hierarchic demand system (Suryanarayana, 1992) for India. The system has many desirable properties that a demand system should have. It attempts to capture household preferences across both food and non-food commodity items. It is a complete demand system based on a nested AIDS-TRANSLOG-LES cost function and is estimated separately for both rural and urban India. Projections based on this system are given in Table A-II.

Table A-II: *A 3-level Hierarchic System Based Demand Projection for India-2050*

Commodity	Units	Projected Demand	Demand (Per Capita) (Total)
Rural India			
Rice	kgs	—	-454.56
Wheat	kgs	—	-309.60
Coarse Grains	kgs	—	-120.00
Dairy Products	kgs	—	465.00
Animal	Rs.	—	717.52
Urban India			
Rice	kgs	128815.50	126.40
Wheat	kgs	101912.70	100.00
Goarse Grains	kgs	73250.01	71.88
Dairy Products	kgs	492238.30	482.00
Animal Products	kgs	1003055.00	984.23

While for the rural sector, the projections are clearly absurd, for the urban sector it gives very high demands. Thus it is not enough to have a complete expenditure system. It should also be robust over large changes in income and expenditure.

The problems with these projections is that the implied calorie intake is too high to be physiologically credible. They imply whole nations of obese gluttons. What is needed is a demand projection method that respects some caloric constraint. Fortunately, the demand system used in some of the national models of IIASA's basic linked system (BLS) have such a feature. In these models, a linear expenditure system is synthesized at each expenditure level given a set of prices. This involves the following steps :-

1) A modified "Engel Curve" which expresses per capita demand as a function of per capita expenditure as well as own price of the commodity is estimated for each commodity for the historical data of the country. Thus,

   $D_i = f_i\ (e, p_i),$

   where d_1 is per capita demand for *i*th commodity, P_i is price of *i*, and *e* total per capital expenditure.

2) An Engel Curve for aggregate calorie intake is also estimated from cross country data. This curve is asymptotic to a level of 4500kcal/capita/per day.

3) Form these Engel Curves we estimate the demands d_i for all commodities and aggregate calorie for an estimated expenditure level $\hat{e}$ and assumed price P_i In general, the demand do not add up to the projected expenditure i.e., in general,

   $$\Sigma p_i\ \hat{d}_i \neq \hat{e}$$

   Also in general, the implied calorie intake would not add up to the projected calorie intake C^, i.e., with c_i the calorific value of *i*th commodity:

   $$\Sigma c_i\ d_i \neq \hat{c}$$

4) Find a vector (*d*) such that the weighted distance between (*d*) ($\hat{d}$) is minimized subject to the conditions that the total expenditure on (*q*) equals the given total expenditure and the calorie content of (*d*) adds upto $\hat{C}$.

5) Vector (*d*) is the per capita projected demand. Multiply with projected populations to obtain projected total demand.

The details of this approach are given in Fischer *et al.* (1988). Such a system can be looked upon as an approximation to an underlying nonlinear demand system.

OUTLOOK

S. Varadarajan

Food and Energy Security are major factors for attention in a period of growing population and urbanisation in India. Economic growth of a high order is essential to ensure better health, habitat and environment. India has the second largest population in the world. Many of the people are young aspiring for an assured bright future to participate actively in Development. New opportunities for gainful employment in rural and urban areas have to be evolved.

The articles record successes in meeting the large demands for health, food, nutrition, water, energy in five decades and especially in the past twenty years from a high degree of self-reliance from Indian Science and Technology within the valuable framework of freedom. The State has provided support and system for such scientific evolution of relevance in the public domain and directed application to create a technologically powerful democratic base, winning the trust of the citizens, while preserving the diversity of culture and growing equality.

There is now confidence to encourage entry into freer competition in World Trade and in Intellectual Property Rights. Entirely new international Standards on environment have been readily accepted. The requirements for energy, especially petroleum oil and gas are large and have to be met by imports. New technologies for rigorous fuel quality standards have to be generated and applied. Security for safety against hazards in hydrocarbon storage, transfer, process, distribution have to be increased. Mechanisms to meet disruptions in availability of these products are essential.

These create novel challenges for Science and Technology as well as new avenues to ensure Food and Energy Security and high growth in many areas of manufacture and services,, while preserving the environment, traditional values and inherited rich biodiversity. These are the components for Sustainable Development. International advances in Science are extremely rapid and not readily foreseen. Their application is virtually in real time with no delay. New knowledge, replacing rapid obsolescence is the crucial capital resource in the highly competitive new world.

The contributions collected in this volume provide a perspective of the needs and opportunities. There are clearly excellent array of potential resources from which choices could be made for Development in the decade ahead and beyond. The State and the Leadership have to refashion the Scientific System to promote creativity, enterprise, courage and daring as in other democracies. Greater interaction with social sciences and venture capital for national profit is vital. India can, not only overcome uncertainties and ensure security to meet all needs but plant the seeds for a Evergreen Economic Revolution.